# A Heat Transfer Analysis of the Fiber Placement Composite Manufacturing Process

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**ABSTRACT:** A computer code is developed to accurately simulate the three-dimensional heat transfer during the thermoset fiber placement composite manufacturing process. The code is based on the Lagrangian formulation of the problem. Eight-node brick elements are employed, and the  $2 \times 2 \times 2$  integration rule is used to numerically evaluate the integrals over an element. The coupled ordinary differential equations obtained by the semidiscrete formulation of the problem are integrated by the unconditionally stable backward difference method. The code is validated by comparing the computed results for several problems with those available in the literature. Composite rings are manufactured by continuously laying a tape over a cylindrical mandrel and the temperature histories at several points are measured with thermocouples. The computed temperature distribution is found to compare well with the test findings. The code can be used to optimize the processing variables.

KEY WORDS: fiber placement, finite element analysis, manufacturing.

# **INTRODUCTION**

THE PROCESS MODELED here consists of laying down a unidirectional prepreg tape on the surface of a mold by a moving head comprised of a heater and a roller

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Figure 1. Schematic diagram of the tape laying process.

(see Figure 1). The former supplies the heat and the latter, the required pressure. The consolidation head moves with a speed V, which causes the temperature and stress variations to be induced in the part being manufactured as a function of time and position.

A number of heat transfer models have been proposed for investigating the thermal history of fiber placement [1-10] and filament winding [11-16]. The techniques used are classified into two categories. In the first one, a quasi-steady state is assumed to prevail throughout the process, and the steady-state heat transfer problem in the Eulerian framework [1-5,9-13] is analyzed; and the transient heat conduction equation in the Lagrangian framework [6-8,14-16] is solved in the second.

Grove [1] developed a two-dimensional finite element (FE) model to investigate the temperature profile of the tape laying process with a single laser heat source. The region close to the tape-substrate interface was modeled using a coordinate system fixed to the layup head and moving with it. Thus, the problem could be solved by using a fixed FE mesh. Furthermore, the movement of the lay-up head was modeled by incrementally shifting the calculated temperature distribution throughout the mesh at appropriate time intervals. Nejhad et al. [3,9] used a finite difference (FD) method to show that very high temperature gradients existed near the nip point, and that the roller speed, heat input, and preheating significantly affected the temperature field in the laminate. A control volume, which includes the region influenced by the local heat source, was chosen and the problem was formulated as steady-state using an Eulerian approach. Results were computed for a flatbed fiber placement process [3] modeled as a two-dimensional problem, and for the filament winding process [9] modeled as a three-dimensional problem. James and Black [11,12] investigated the continuous filament winding process employing an infrared energy source. They also transformed the transient thermal problem into a quasi-steady one in an Eulerian frame. The one-dimensional heat transfer analysis of the tape regime was coupled to the three-dimensional heat transfer analysis of the composite-mandrel assembly. The explicit FD method was used to solve the problem numerically. For both the fiber placement and the filament winding processes, a point in the laminate experiences a series of thermal impulses (rapid heating followed by slower cooling), which decreases in magnitude as successive plies are added [1]. Sonmez and Hahn [4,5] investigated the temperature history and the crystallinity developed during subsequent lay-ups of the fibers. Loos and Song [13] have computed thermal histories at a point in a filament wound composite ring.

Springer and his coworkers [6,7,14] have developed the two-dimensional thermochemical models to ascertain the temperature, the degree of cure (for thermosetting matrix composites) or the crystallinity (for thermoplastic matrix composites), and viscosity inside the composite for both tape laying and filament winding processes. The lay-up process was simplified by assuming that the top layer is laid down instantaneously along the entire length of the composite and the lay-up head then moves along the top surface of the layer to consolidate it onto the substrate. The time history of the thermochemical variables was computed by the FE method. An implicit backward difference method was used to integrate, with respect to time t, the coupled ordinary differential equations arising from the semidiscrete formulation of the problem. Pitchumani et al. [8] also used the twodimensional transient heat transfer model to optimize the thermoplastic tow-placement process. Shih and Loos [15,16] used the commercial FE package, ABAOUS, to study the transient heat transfer problem associated with a continuous filament winding process using a hot-air heater. Assuming that very little energy propagates across the interface between the compaction roller and the composite substrate, they found the temperature profile in the substrate cylinder and the towpreg prior to its reaching the nip-point.

We note that the problem is really three-dimensional since during continuous placement of the towpreg, heat is conducted in all the three directions. Here we present such a model with the following unique features: (i) continuous laying of the tape rather than the entire layer being laid down instantaneously and (ii) three-dimensional heat transfer problem including heat conduction in the tool and heat exchange through convection with the surroundings.

## FORMULATION OF THE PROBLEM

A mold with its upper surface partially covered by the prepreg tape of width w is shown in Figure 2. During the ensuing time interval  $\Delta t$ , a piece of tape of length  $\Delta l$  is laid next to the end of the prepreg tape and thermal energy at the rate  $\dot{Q}$  is supplied to this piece and to a small area surrounding it. The size of this area depends upon the speed of hot air coming out of the heater nozzle, the distance of the nozzle from the mold, and the inclination of the heater nozzle with respect to the mold. The speed V of the moving head equals  $\Delta l/\Delta t$ . After the entire top surface of the mold has been covered with the towpreg tape, the direction of tape placement is reversed. That is, the towpreg moves West from the



Figure 2. Mold with the top surface partially covered by the prepreg tape.

Northeast corner. The goal is to find the temperature distribution as a function of time *t*; hence the mold and the prepreg tape are regarded as rigid bodies.

The heat transfer is governed by the transient heat conduction equation with heat generation:

$$\rho c_p \dot{T} - (k_{ij} T_{,j})_{,i} - \dot{Q}_1 - \dot{Q}_2 = 0 \quad \text{in } \Omega, \tag{1}$$

where  $\rho$  is the mass density,  $c_p$  the specific heat,  $\dot{T}$  the rate of change of temperature at a material point,  $k_{ij}$  the thermal conductivity tensor,  $\dot{Q}_1$  the rate of heat generated per unit volume due to exothermic chemical reactions that occur during curing of the resin,  $\dot{Q}_2$  the rate of energy supplied to a unit volume of the prepreg tape by the heat source, and  $\Omega$  is the region of space occupied by the body. Here  $T_{,i} = \partial T/\partial x_i$ ,  $\dot{T} = DT/Dt = \partial T/\partial t$  since we are using the Lagrangian description, and a repeated index implies summation over the range of the index.

The boundary conditions include either prescribed temperatures, or heat transfer due to convection. That is

$$T = \hat{T} \quad \text{on } \Gamma_u, \tag{2}$$

$$-k_{ij}T_{,i}n_i = h(T - T_{\infty}) \quad \text{on } \Gamma_t,$$
(3)

where  $\hat{T}$  is the prescribed temperature, *h* is the coefficient of convective heat transfer, *n* is an outward unit normal to the surface, and  $T_{\infty}$  is the ambient temperature.  $\Gamma_u$  and  $\Gamma_t$  are parts of the boundary  $\Gamma$  of  $\Omega$  where the temperature and the heat flux are prescribed, respectively. For a thermally insulated surface, h=0. The value of *h* is a function of the hot air speed and possibly its temperature; however, it is taken to be a constant here.

The material of the prepreg tape is assumed to be orthotropic. For the coordinate axes aligned with the material principal axes, the conductivity matrix  $k_{ij}$  is diagonal. When the axes of material symmetry in the plane of the tape make an angle  $\theta$  with the global  $x_1$  and  $x_2$  axes, and the transverse direction of the tape is along the  $x_3$ -axis, the nonzero terms in the conductivity matrix are

$$k_{11} = k_L \cos^2 \theta + k_T \sin^2 \theta, \tag{4}$$

$$k_{12} = (k_L - k_T)\sin\theta\cos\theta, \qquad (5)$$

$$k_{22} = k_L \sin^2 \theta + k_T \cos^2 \theta, \tag{6}$$

$$k_{33} = k_T. \tag{7}$$

Here  $k_L$  and  $k_T$  denote respectively the thermal conductivities along the length of the fiber and perpendicular to it.

The essential boundary condition (2) is imposed on the bottom surface of the mold, and natural boundary conditions (3) are applied on the remaining bounding surfaces of the composite body. Note that the edge BC of the prepreg tape will occupy a different position in space as the next piece of the prepreg tape is laid down.

The prepreg tape is assumed to contain a thermosetting polymeric resin. An increase in temperature causes the resin to cure, and heat is generated by exothermic chemical reactions during the curing of the resin. On the assumption that the rate of heat generation during cure is proportional to the rate of the cure reaction, the degree of cure,  $\bar{\alpha}$ , of the resin can be defined as

$$\bar{\alpha} = \frac{H(t)}{H_R},\tag{8}$$

where H(t) is the heat evolved from the beginning of the reaction to the present time t, and  $H_R$  is the total heat of reaction during complete cure of the resin. Differentiation of Equation (8) with respect to time and the rearrangement of terms give

$$\dot{H} = \frac{d\bar{\alpha}}{dt} H_R \tag{9}$$

where  $d\bar{\alpha}/dt$  is the reaction or the cure rate. An expression for the cure rate of a thermosetting resin, which is a function of temperature and degree of cure, is

$$\frac{d\bar{\boldsymbol{\alpha}}}{dt} = f(T,\bar{\boldsymbol{\alpha}})(1-\bar{\boldsymbol{\alpha}})^n \tag{10}$$

where the function  $f(T, \bar{\alpha})$  depends on the type of reaction and *n* is the reaction order. The function *f* is usually of the form:

$$f(T,\bar{\alpha}) = k_1 + k_2 \bar{\alpha}^m \tag{11}$$

where  $k_1$  and  $k_2$  are the rate constants, and *m* is a kinetic exponent. The temperature dependence of the rate constants is given by an Arrhenius-type expression:

$$k_i = A_i \exp\left[\frac{-E_i}{RT}\right], \quad i = 1, 2,$$
(12)

where  $A_i$  is the Arrhenius pre-exponential factor,  $E_i$  the Arrhenius activation energy, and R the gas constant. Values of these constants can be found by using a procedure similar to that given in [17]. If diffusion of chemical species and convection of the fluid are neglected, then the degree of cure at each material point can be determined by integrating the cure rate with respect to time.

# NUMERICAL SOLUTION

The three-dimensional heat transfer problem formulated above is solved by the finite element method. The domain of study is discretized into eight-node brick elements. The Galerkin approximation of the problem is derived as follows:

Multiplication of both sides of Equation (1) by a test function  $\Phi$  that vanishes on  $\Gamma_u$ , integration of the resulting equation over the domain  $\Omega$ , and the use of the divergence theorem give

$$\int_{\Omega} \rho c_p \dot{T} \phi \, d\Omega + \int_{\Omega} k_{ij} T_{,j} \phi_{,i} \, d\Omega + \int_{\Gamma_t} h T \phi \, d\Gamma = \int_{\Gamma_t} h T_{\infty} \phi \, d\Gamma + \int_{\Omega} \phi (\dot{Q}_1 + \dot{Q}_2) d\Omega.$$
(13)

Recall that

$$\int_{\Omega} (\cdot) \, d\Omega = \sum_{e} \int_{\Omega_{e}} (\cdot) \, d\Omega \tag{14}$$

where  $\Omega_e$  is an eight-node brick element in  $\Omega$ . On an element  $\Omega_e$ , the temperature is assumed to be given by

$$T(x_1, x_2, x_3, t) = \sum_{A=1}^{8} N_A(x_1, x_2, x_3) T_A(t),$$
  

$$\phi(x_1, x_2, x_3) = \sum_{A=1}^{8} N_A(x_1, x_2, x_3) C_A,$$
(15)

where  $N_1, N_2, \ldots, N_8$  are shape functions,  $T_1, T_2, \ldots, T_8$  are time-dependent temperatures of eight-nodes, and  $C_1, C_2, \ldots, C_8$  are constants. Substitution from Equations (14) and (15) into Equation (13) and recalling that the function  $\phi$  is arbitrary we arrive at the following set of coupled ordinary differential equations for the determination of the nodal temperatures:

$$\mathbf{MT} + \mathbf{KT} = \mathbf{F}.$$
 (16)

Here

$$\mathbf{M} = \sum_{e} \mathbf{M}^{e}, \quad \mathbf{K} = \sum_{e} \mathbf{K}^{e}, \quad \mathbf{F} = \sum_{e} \mathbf{F}^{e},$$

$$M_{AB}^{e} = \int_{\Omega_{e}} \rho c_{p} N_{A} N_{B} d\Omega,$$

$$K_{AB}^{e} = \int_{\Omega_{e}} k_{ij} N_{A,j} N_{A,i} d\Omega + \int_{\Gamma_{i} \cap \Omega_{e}} h N_{A} N_{B} d\Gamma,$$

$$F_{A}^{e} = \int_{\Gamma_{i} \cap \Omega_{e}} h T_{\infty} N_{A} d\Gamma + \int_{\Omega_{e}} N_{A} (\dot{Q}_{1} + \dot{Q}_{2}) d\Omega.$$
(17)

**M** is the heat capacity matrix, **K** is the conductivity matrix, and **F** is the load vector.

The coupled ordinary differential equations (16) are integrated for nodal temperatures by an unconditionally stable backward difference scheme. For a given speed of the moving head, the time step size  $\Delta t$  used in the backward difference integration scheme is related to the length  $\Delta l$  of the piece of the prepreg tape just being laid down. Both  $\Delta t$  and  $\Delta l$  can be adjusted to compute the temperature field within the prescribed accuracy. The application of the backward difference formula to Equation (16) results in a system of simultaneous linear algebraic equations for the nodal temperatures. Essential boundary conditions are enforced by the penalty method and equations are solved for nodal temperatures.

A three-dimensional finite element code, FBPLACE, is written in the modular form to simulate the fiber placement process. The code solves the system of equations governing the heat transfer and incorporates heat generated due to curing and different types of boundary conditions. It uses eight-node brick elements, the eight-point Gauss integration

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rule, and the lumped mass matrix. A direct sparse solver is used to solve the set of linear algebraic equations. The code has a data base of material models that contains values of various material parameters needed for each analysis. Input and output formats for all models are based on the neutral file concept of the solid modeling package PATRAN. The code has been verified by comparing the computed results for several problems with their analytical solutions; an example is given here.

Consider the transient heat conduction in a rod of 1 m length with no heat generation. The temperature at the left end of the bar is specified to be zero and a convection boundary condition is applied to the right end of the rod. That is,

$$T = 0 \quad x = 0, \quad t \ge 0$$
  
$$-k\frac{\partial T}{\partial x} = h(T - 0) \quad x = 1, \quad t \ge 0$$
 (18)

The initial temperature distribution in the rod is expressed as

$$T_{t=0} = \begin{cases} 4000x & 0 \le x \le 0.025\\ 100 & 0.025 \le x \le 1.0 \end{cases}$$
(19)

The problem can be solved by the method of separation of variables as given in [18]. The finite element solution was compared with the analytical solution of the problem in Figure 3. It is clear that the two solutions essentially coincide with each other.

For the tape laying process, the three-dimensional temperature distribution in the tape element and the mold were computed with FBPLACE and the commercial code ABAQUS after only one element had been placed on the mold. Again the two solutions were found to agree with each other.



Figure 3. Comparison of the finite element and the analytical solutions of heat conduction in a bar.

#### **EXPERIMENTAL**

In order to validate and verify the theoretical model, composite rings were manufactured by laying a prepreg tape on a cylindrical mandrel. Except for the difference in the geometry, this process has all the ingredients of the one used to manufacture flat and curved parts. Critical parameters include the heat supplied to the prepreg tape and the pressure applied at the nip point. Heating the prepreg tape causes the resin to soften and flow, which permits deformation of the resin-saturated fiber tow. Overheating of the prepreg during lay-up will result in too much resin flow and excessive nip point pressure can cause large transverse deformation.

The fiber placement facility is schematically illustrated in Figure 4 and includes a prepreg delivery system, a computer-controlled filament winding machine, and a consolidation head assembly. Figure 5 shows a photograph of the consolidation head assembly. The prepreg enters from the right from the tension controller, and passes through the two white Teflon and two aluminum guide rollers before exiting onto the mandrel surface. The large black cylinder between the two sets of rollers is an infrared thermometer and is used to measure the surface temperature of the incoming prepreg. The horizontal silver cylinder toward the bottom of the crosshead is a pneumatic cylinder attached to the 25.4 mm (1 in.) diameter steel compaction roller. The cylinder can produce a nip-point force of 442.2 N (99.4 lb) at 689.5 kPa (100 psi) air pressure. The cylindrical component located at the upper left hand corner of Figure 5 is the hot gas heater. Dry, compressed air is heated and ejected through the nozzle at the bottom. The maximum air temperature is  $870^{\circ}$ C (1600°F). At the end of the armored cable leading to the nozzle is the thermocouple that reads the exiting air temperature. The air temperature is controlled by a proportional integral derivative controller. The aluminum mandrel is 146 mm (5.75 in.) in diameter and 152.4 mm (6 in.) in length.

The filament winding machine is able to control spindle rotation and linear carriage motion. A personal computer is used to provide supervisory control, display information, and store and load the machine's motion and control program. Winding patterns are generated off-line by CADWIND<sup>TM</sup> pattern generation software.



Figure 4. Illustration of the fiber placement facility.



Figure 5. Consolidation head assembly.



Figure 6. Thermocouples embedded in the composite ring during lay-up.

An in situ measurement system was constructed to acquire thermal data during the lay-up process. The temperature measurements during fiber placement were obtained by using a nine-channel slip ring assembly installed on the spindle of the mandrel. Figure 6 shows several thermocouples embedded in the composite lay-up. For this project, a maximum of eight K-type, fast-responding thermocouples were used. Because of the rapid

temperature changes during the process, a data acquisition with a high sampling rate was required. A PC-based data acquisition (DAQ) system was selected which consisted of the computer, the SCXI signal conditioning modules, the DAQ board, and National Instruments' LabVIEW software. Additional details of the fiber placement and data acquisition systems can be found in [21].

Composite specimens were fabricated from Cytec-Fiberite IM7/977-2, graphite fiber/ epoxy resin slit tape. The uncured towpreg was 3.175 mm wide and 0.16 mm thick. The composite lay-ups were 32 plies thick and were wound on an aluminum mandrel with an outer diameter of 146 mm (5.75 in.). All of the composite rings were hoop wound and were either 3.175 mm or 25.4 mm in length.

The parameters that can be directly controlled during lay-up are heater air temperature, heater airflow rate, mandrel speed, roller pressure, and distance between the heater nozzle and the nip point. Of these, the heater airflow rate and distance from the nozzle to the nip point were fixed and held constant for ring production. Heater gas temperature, mandrel speed, and roller pressure were varied.

The baseline parameters that were selected were as follows. A temperature of  $121^{\circ}$ C (250°F) was found to provide adequate resin flow under compaction without adhering to the roller. A pressure of 345 kPa (50 psig) applied to the compaction roller was found to yield good compaction without excessive deformation of the composite substrate. The mandrel speed was found to be inconsequential compared to the roller pressure and heater gas temperature. A standard speed of 6 rpm was chosen. The pressure of the air supplied to the heater was set at 55 kPa (8 psig). The distance from the nozzle of the heater to the nip point, and the angle of the heater were set to provide uniform heating of the prepreg and composite substrate at the nip point while maintaining sufficient clearance between the nozzle and the composite.

#### RESULTS

In simulating the fiber placement process, the motion of the fiber placement head must be considered. The computer code FBPLACE uses the Lagrangian description in which one follows a set of fixed material particles. The hot gas heater, modeled as a convective boundary condition, moves along the mandrel–composite substrate. The speed of the head is modeled by incrementally moving the heat source around the outer surface of the composite as shown in Figure 2. The computational procedure is as follows:

- 1. Construct a finite element mesh of the tool and the entire composite laminate;
- 2. Initially, at time equal to zero, apply boundary conditions to the tool only;
- 3. At each time step, add a new composite element;
- 4. Modify the boundary conditions as each new element is added;
- 5. Calculate the temperature distribution at each time step; and
- 6. Once the temperature distribution is known, calculate the resin degree of cure.

Figure 7 shows the finite element mesh (mesh 1) of the composite ring and the entire mandrel assembly. The aluminum mandrel has an inner diameter of 134 mm, an outer diameter of 146 mm, and is 152.4 mm long. There are three layers of elements through the thickness, 32 elements in the circumferential direction, and 48 elements along the length for a total of 4608 elements. For the composite lay-up, there are 32 layers of elements through the thickness. Each layer is 0.16 mm thick and 3.175 mm wide. A total of 1024 elements were used to represent the composite.



Figure 7. Finite element mesh for the composite ring and the entire mandrel (mesh 1).



Figure 8. Finite element mesh for the composite ring and section of the mandrel (mesh 2).

The finite element mesh of the entire aluminum mandrel and composite ring is quite large. In order to reduce the computation time required for a complete winding simulation, a mesh with a reduced number of elements was generated as shown in Figure 8 (mesh 2). The simplified mesh includes only the portion of the mandrel that the composite ring is wound onto and the number of elements is reduced to 1120.

The temperature versus time profiles for the two finite element meshes are compared in Figure 9 for a single point at the mandrel–composite interface. From the figure it can be seen that the temperature versus time profiles are almost identical for the two meshes. The temperatures at other points within the composite lay-up compared well for the two meshes. Henceforth, the smaller of the two meshes (mesh 2) was used for the remaining simulations.

The surface area of the mandrel impinged upon by the hot air was determined as follows: Eight equally spaced thermocouples were mounted both in the axial and in the circumferential directions on the mandrel. Hot air from the heater was blown on the mandrel and readings of the thermocouples were recorded. It was estimated that the hot air affected a circular region of radius 9.5 mm centered at the center of the air nozzle. During the computation of results presented here, the temperature of the hot air and the heat transfer coefficient, h, between it and the mandrel and that between the hot air and the prepreg tape were assumed to be the same constants. Furthermore, h was taken to be independent of the temperature.

Figure 10 shows the calculated temperatures as a function of time during lay-up of a 32-ply thick composite ring using the baseline processing parameters. The temperatures of points in layers 2, 10, 20, and 30 are shown. The temperature is the highest when the layer is initially wound onto the composite substrate and then gradually decreases with time as additional layers are added to the composite. Note that the peak temperature of the top layer increases as the thickness of the composite increases and it becomes closer to the nozzle of the hot gas heater. This is because the towpreg is now being laid over a warmer substrate and also the temperature of the air impinging on it is a little higher because of the slightly smaller distance between the nozzle and the composite part.

Thermocouples were embedded in different layers during the manufacturing process. Figure 11 exhibits locations of four thermocouples used in the experiment. Note that the thermocouples are mounted on the surface of the mandrel. The value of the convective



Figure 9. Comparison of the temperature vs time profiles for the two meshes.



Figure 10. Layer temperatures as a function of time during lay-up of a 32-ply composite ring.



Figure 11. Thermocouple locations on the surface of the mandrel.

heat transfer coefficient used in the simulation model was estimated by assuming a value and comparing the temperature versus time profiles with the measured values. This process was repeated until the predicted temperature profile agreed with the measured profile. The results for two measured temperature locations are shown in Figure 12 for thermocouple 6 and Figure 13 for thermocouple 7. From the results it can be concluded that simulations with a convection coefficient of  $350 \text{ W/m}^2 \,^\circ\text{C}$  predicted temperatures that were closest to the measured values.

Three additional simulations were performed to verify the model and delineate the effect of the winding speed and the hot air temperature on the composite temperature. Shown in Table 1 are the values for the parameters that were varied. A convection coefficient of  $350 \text{ W/m}^2 \,^{\circ}\text{C}$  was used for all the simulations.

#### "Thermocouple 6"



Figure 12. A comparison of computed and measured temperatures at thermocouple 6 for different values of the convective heat transfer coefficient.

"Thermocouple 7"



Figure 13. A comparison of computed and measured temperatures at thermocouple 7 for different values of the convective heat transfer coefficient.

Case	Air temperature (°C)	Winding speed (rpm)
1	121	6
2	121	3
3	150	6

Table 1. Parametric studies.



Figure 14. A comparison of the computed and the measured temperature vs time histories at the location of thermocouple 5 for case 1.

The computed and measured temperature versus time history at thermocouple location 5 is shown in Figure 14 for the baseline processing conditions (Case 1). Except for winding of the first layer, the peak predicted temperatures match the measured values very well. Overall, there is good agreement between the calculated and measured temperature versus time profiles for the 32 layers. The effect of reducing the winding speed on the temperature versus time profile can be observed by comparing data in Figures 14 and 15. At the lower winding speed of 3 rpm, the measured peak temperatures during winding of the first four layers were as much as 10°C higher than predicted. This is most likely due to the transient effects during the beginning of the winding process. After layer number four, the calculated and measured peak temperature versus time history. By the end of the winding process, the measured temperature versus time history is one complete cycle ahead of the predicted temperature versus time history. This is due to the poor control of the mandrel speed at low rpm. At the end of the winding process, the peak temperatures are about 33 and 35°C for winding speeds of 6 and 3 rpm, respectively.

The effect of increasing the hot gas heater air temperature can be observed by comparing the results given in Figures 14 and 16. An increase in the air temperature of  $20^{\circ}$ C results in about a 3°C rise in the peak temperature at a point in the composite.



Figure 15. A comparison of the computed and the measured temperature vs time histories at the location of thermocouple 5 for case 2.



Figure 16. A comparison of the computed and the measured temperature vs time histories at the location of thermocouple 5 for case 3.

Figure 17 exhibits the temperature variation in the radial direction within the composite cylinder at the conclusion of manufacturing a 32-layer composite ring. The temperature varies very gradually within the mandrel since it is a good conductor of heat but varies rapidly in the composite cylinder. However, the temperature difference between the outermost and the innermost layers is less than  $2.4^{\circ}$ C. If the temperature variation in the



Figure 17. Radial temperature distribution at the completion of the winding process.



Figure 18. Finite element mesh for the sine wave tool and the composite laminate.

manufactured part is taken as an indicator of the quality of the part produced, then the 32-layer ring should be of good quality.

The placement of a prepreg tape on the surface of a sine wave tool was simulated with the computer code FBPLACE. Figure 18 shows the finite element mesh for the 1 m long and 0.5 m wide aluminum tool divided into 1600 elements. The composite laminate was 8 plies thick and had 400 elements per ply.

The cure kinetics model for Hexcel AS4/3501-6 carbon/epoxy prepreg was used in the simulations [22]. Figure 19 depicts time histories of the temperature and the degree of cure at the point located at the geometric center of layer 1. Note the eight temperature spikes in the figure. The spike occurs first during initial lay-up of the towpreg (the highest temperature predicted) and then seven more times as subsequent layers are placed and the hot gas torch passes over the first layer. At the end of the fiber placement, a degree of cure of 0.076 is predicted. Figure 20 shows the degree of cure distribution in layer 1 after the completion of the lay-up process. Information on the degree of resin cure in the composite after lay-up is important in assessing if the resin is sufficiently staged so that the high temperature cure can proceed without excessive resin flow.



History of temperature and cure for centerpoint of layer 1

Figure 19. Time history of the temperature and the degree of cure at the geometric center of the top layer.



Figure 20. Distribution of the degree of cure in layer 1 upon completion of fiber placement.

#### CONCLUSIONS

A major objective of the research program was to develop a comprehensive simulation model of the fiber placement composite manufacturing process. Initial work has focused on modeling the two-step process commonly used today with thermoset prepreg tape. In the two-step process, the structure is cured in a separate step after lay-up.

A three-dimensional finite element code to analyze heat transfer in the tape laying process was developed. Unique features of the model are: (i) continuous laying of the tape rather than the entire layer being laid down instantaneously and (ii) three-dimensional heat transfer, including heat conduction in the tool and heat exchange through convection with the surroundings.

In order to validate and verify the theoretical model, composite cylinders were manufactured by laying a prepreg tape on a cylindrical mandrel. The temperatures were measured during fiber placement by thermocouples embedded in the composite substrate. Overall, the measured temperatures agreed well with the model predicted values. Reasons for small differences between the measured and the computed results include (i) approximations made to estimate the heat transfer coefficient between the hot air and the prepreg tape and that between the hot air and the tool surface, (ii) error in estimating the surface area of the cylinder affected by the hot air, (iii) thermal conductivities of the prepreg tape in three principal material directions, (iv) temperature of the hot air impinging upon the tape and the tool, (v) neglecting of the increase in the temperature of the prepreg tape as it is laid on the composite substrate, (vi) neglecting heat conducted away from the part being manufactured to the parts supporting the mandrel, (vii) variations in the mandrel speed, and (viii) neglecting the dependence of material properties upon the temperature. Future work will refine the model and consider these effects.

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