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FIBER PLACEMENT DEVELOPMENTS AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

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Introduction

The Composites Workstation (CWS) of NIST's Automated Manufacturing Research Facility was initiated to develop the means to fabricate complex shaped components using continuous fiber composite material [1]. To fabricate the complex shapes, the Composites Workstation elected to pursue the relatively new fabrication process known as *Fiber Placement*. In response to industry interests, carbon/PEEK (APC-2/AS4) was selected as the thermoplastic prepreg. A major manufacturing advantage of thermoplastic prepreg stems from the ability to consolidate the thermoplastic immediately upon laying the material on the part form. This procedure is called *in-situ consolidation*. Successful in-situ consolidation would dramatically enhance the economical manufacture of thermoplastic composites and achieving sufficient compaction is fundamental to successful consolidation.

Fiber placement is the confluence of filament winding and tape laying. Similar to filament winding, fiber placement uses multiple tows of continuous composite material. In fiber placement these pieces are generally pre-impregnated composites and are placed with high accuracy, similar to tape-laying. The combination of tape laying and filament winding yields a process which can produce shapes which are too complex for either filament winding or tape laying.

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Composite parts manufactured with tape-layers are large with relatively minor concave and convex surface contours. Parts made by filament winding are convex shapes with generally one (although some machines allow for two) axis of rotation. The first fiber-placement machines were successful in winding composite materials on concave shapes along non-geodesic paths [2]. The axis of rotation requirement was also greatly reduced. Candidate parts were only required to have an approximate axis of rotation. However, parts with multiple axes of rotation or deep recesses remain excluded from automated manufacture.

These initial fiber-placement machines followed the industry practice of using thermoset composites. There has been an enormous interest in industry in substituting thermoplastic composites for thermosets in some applications. Thermoplastics have several advantages in their final form and major potential advantages in manufacturing. Unlike a thermoset, which must be separately cured in an autoclave, thermoplastics can be consolidated during the initial assembly. This feature, called in-situ consolidation, can greatly reduce the manufacturing cost of composite parts. A successful in-situ consolidation process is very complex involving several fixed and controllable parameters. The initial intention of the Composite Workstation was to adopt an existing process from industry.

After several months of effort, the members of the project were unable to locate a suitable in-situ consolidation process. Most processes investigated could not be utilized with fiber placement. Other processes were either cost-prohibitive or unavailable due to proprietary content. Therefore, the primary work of the workstation, i.e., producing parts with complex geometries, was delayed while an existing process was refined for our use.

The available systems consisted of a heat source and a compaction device. As shown in figure 1, the heat source elevates the temperature of the new tow and the substrate as they join at the nip, then the compaction device presses the new tow and substrate together. The heat sources were laser, focused infrared, hot gas, hot shoe, and ultrasonic. The compaction device was generally a simple stainless steel roller. In a basic system, the heating device brings the tow up to processing temperature then the compaction device pushes the melted tow onto the substrate. The polymer then cools into a single thermoplastic matrix. Although the design of equipment to perform this process is straightforward, the conventional designs initially tested yielded unsatisfactory results.

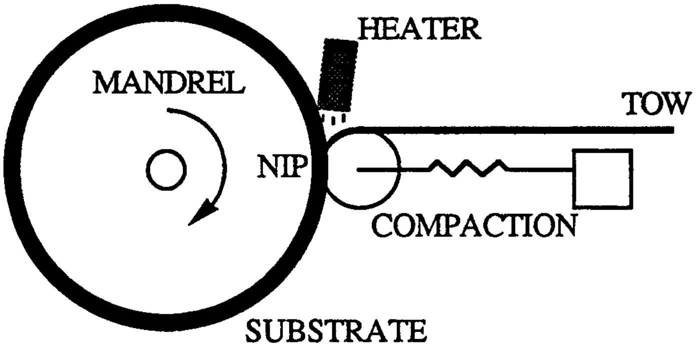


Figure 1. Basic In-Situ Consolidation System

The immediate goal of the Composites Workstation was to determine the necessary parameters for successful compaction and build a system to implement these parameters. Compaction is one portion of consolidation. In particular, compaction deals with the elimination of voids. The other aspects of consolidation, such as crystallinity, will be addressed in the future.

Theory

The theoretical model of the mechanisms involved in in-situ consolidation are not fully developed. In new, complex systems, the initial numerical models are developed from observations of experimental data [3].

Once the parameters are identified, a logical grouping of the parameters is then derived and used to better understand the process.

Experiments with APC2/AS4 have shown solid correlations between the amount of compaction and three parameters: the pressure applied, the processing temperature, and the laydown rate. Researchers at the Georgia Institute of Technology have proposed a dimensionless *Compaction Number* [4] to demonstrate how these parameters interact. Georgia Tech's Compaction Number is based on a fluid mechanics model and is the ratio of the Reynolds number and the Euler Number. The number is given by:

$$CN = \frac{\Delta p\ L}{V\ \mu} \qquad (1)$$

where L is the compaction length, V is the velocity, Δp is the change in the static pressure in the fluid, and μ is the viscosity.

The most significant aspect to achieving successful compaction is the flow of the matrix material. For this analysis, the melted PEEK is considered an incompressible fluid. Forces exerted in an incompressible flow are the inertia force, viscous forces, and the pressure [5]. Expressed in standard numbers, these forces are represented in the dimensionless Reynolds and Euler numbers. The Reynolds Number is generally used to characterize the velocity profile in a fluid and is the ratio of the fluid velocity and the shear velocity. The applicable equation for the Reynolds number is

$$Re = \rho LV/\mu \qquad (2)$$

where ρ is the density of the fluid. The Euler Number, sometimes called the pressure coefficient, is the ratio of the pressure to the inertial forces. The equation is

$$Eu = \rho V^2/\Delta p\,. \qquad (3)$$

Obviously, the formulation of the Compaction Number assumes a correlation between the fluid velocity and the laydown rate.

In a fiber placement process, a laydown head containing the heat and pressure sources moves along the substrate surface adding the prepreg tow. The pressure and the temperature are, therefore, functions of the velocity of the laydown head, and are subsequently functions of time. The matrix's viscosity is, as will be shown below, a function of temperature, and therefore, is likewise a function of time. The ratio of the length and the velocity yields a time expression. Rearranging the terms of equation (1), and expressing the equation as an integral summation we obtain the Compaction Number equation in a more general form.

$$CN = \int_0^{\tau} \frac{\Delta p(t)}{\mu(t)}\, dt \qquad (4)$$

The relationship between the Compaction Number and the void content of the product must still be established through an analysis of experimental results. Each process is likely to produce a slightly different correlation. However, initial analysis shows an inverse correlation between the two values. That is, as the Compaction Number rises, the void content diminishes. The analysis so far indicates that the Compaction Number is a promising, but not a certain, predictor of void content. Thus, the Compaction Number is used as a guide to the modification of an in-situ consolidation process rather then as an absolute predictor.

To reduce the void content in the final product, one must either: decrease the viscosity, increase the pressure, extend the compaction time, or generate some combination of these. Each of the primary parameters hold both promise and problems. The viscosity is primarily a function of the temperature of the material. The processing temperature and the pressure are commonly kept as high as possible. Permissible increases of temperature and pressure promise only minor improvements to the compaction. Since current processes have compaction times of only a few milliseconds, the compaction time is the parameter subject to the largest change, and promises the greatest improvements.

Springer [6] gives the equation for the viscosity of PEEK as

$$\mu(T) = 1.113 \times 10^{-10} \times e^{19100/T(K)} \qquad (5)$$

Thus, the viscosity is an inverse exponential function of the absolute temperature. A rise in temperature causes a decrease in the viscosity, which increases of the Compaction Number, and creates an expected improvement of compaction. APC-2's manufacturer states the recommended processing temperature for PEEK is 400 °C [7]. The manufacturer also claims that processing above this temperature causes only minor oxidizing degradation of the material (defined as 7 C° change in glass transition temperature in the upper 50 micrometers of the material surface). However, other researchers have reported noticeable damage to the material when processing at temperatures above 435 °C [8]. While further investigations are required to examine the disparity, the CWS has chosen to use the more conservative processing temperature recommended by the manufacturer.

The viscosity of the matrix material is also subject to sheer thinning (a decrease of viscosity when the strain rate increases). The Carreau model is a common rheological model for sheer thinning fluids [9]. It is flexible enough to fit a wide range of viscosity as a function of strain rate curves. The model has been found to be especially suitable for the description of flow curves of molten polymers. In a general form the model is

$$\frac{\mu - \mu_\infty}{\mu_0 - \mu_\infty} = \left(1 + \left(\lambda\dot{\gamma}\right)^2\right)^{-N} \qquad (6)$$

where μ_0 is the zero shear rate viscosity, μ_∞ is the infinite shear rate viscosity, λ is a time constant, and N is a dimensionless constant.

The strain rate is determined by the speed which the compaction pressure is applied. For example, when the tow enters the nip, it first makes contact with the compaction roller. At this point, which is some distance from the substrate, the pressure on the tow is zero. The back tension in the tow and the convex surface of the roller begin to apply a small pressure. When the tow first contacts the substrate the pressure will start to rise rapidly. The maximum pressure is experienced at the nip. Thus, the strain rate may be increased by decreasing the duration of the pressure rise. The duration of the pressure rise may be decreased by decreasing the diameter of the compaction wheel or increasing the laydown rate.

The change in the static pressure makes a linear contribution to the Compaction Number. Unfortunately, the relationship between the change of static pressure and the pressure applied by the compaction head is not fully understood. At lower pressures, experimental results indicate a strong relationship between the applied pressure and the resulting compaction. However, this relationship falters at higher pressures [3]. A possible explanation is that, above some threshold, the individual fibers contact and carry an increasing portion of the applied load. At that point, the change in the static pressure in the melted polymer has less correlation to the applied pressure. While the mechanism of the change in static pressure needs further investigation, based on experimental data, the expected improvements to the compaction from increases in pressure are modest.

Currently, the compaction time in fiber placement systems is, due to the small contact area, on the order of milliseconds. Therefore, the ability to double or triple the Compaction Number by increasing the compaction time is possible. The simplest method to increase the compaction time is to decrease the laydown rate. However, the laydown rate is a major factor affecting the manufacturing cost. In the simplest analysis, the final system should be able to lay composite material at a rate equivalent to manual assembly. Given that the nominal weight of APC-2/AS4 is 213 grams per square millimeter [7], and assuming that the number of tows in the head produces a seventy-five millimeter wide strip and that the manual assembly rate is 0.75 kilograms per hour; a laydown rate of 13 millimeters per second is required. Since all tows in the head do not run continuously, the laydown rate must be substantially faster then 13 millimeters per second to match the manual rate. Thus, reducing the laydown rate is not a viable alternative.

The compaction time may be extended by increasing the length of the compaction area or by making multiple passes over each portion of the substrate. Increasing the compaction length is primarily an engineering design problem. Utilizing subsequent passes over a given section is a matter of processing technique.

Each of the alternatives above for decreasing the viscosity and increasing the compaction time should improve the in-situ consolidation of PEEK composites. However, for the reasons given above, we feel that the most promising approach is to extend the compaction time by lengthening the compaction area.

Approach

This section describes the in-situ consolidation device developed at NIST's Composite Workstation. Work at the workstation began with a simple roller and hot gas compaction system. Various enhancements were then added to improve the final output. The solutions to problems encountered are given in this section along with their justifications. Remaining problems with the approach are reviewed at the end of the section.

As shown in Figure 1, the classic in-situ consolidation system consists of a heat source and a compaction wheel. Incoming thermoplastic tow is added to the substrate at a point called the "nip". As the tow and the substrate approach the nip, they are both heated above the melting point to the thermoplastic's processing temperature. The wheel then pushes the tow onto the substrate, causing their matrix material to diffuse. As the substrate cools the matrix material consolidates into a solid semi-crystalline structure.

To be useful in fiber placement, the size of a consolidation system is restricted. The size restrictions of the CWS are based on two requirements. First, the device must be light enough to be carried by a manipulator. Second, the device must be small enough to fit into the expected recesses. Since the compaction device is being built prior to the manipulator, these constraints provide only general guidance.

Hot air was selected for the heat source. The air heaters selected are small and light weight. They have resistive elements and are rated at 4000 watts. Both the voltage across and the air flow through the elements are controlled to produce the required temperature at a balanced air flow. If the air velocity is too low, insufficient heat is transferred to the material. If the velocity of the air is too high, the air will dismember the fibers when the matrix melts. Approximately 250 milliliters per second at 140 kPa air pressure through a 150 square millimeter nozzle orifice has been an acceptable air flow into the nip.

The initial consolidation system used a single steel compaction wheel. As described in the previous section, increasing the compaction time promised significant improvements in the final product. The goal of the project was, therefore, to find a method to extend the length of contact between the substrate and the compaction "wheel".

After attempting several conformable materials, the traditional compaction wheel was modified to include a recirculating steel band. This approach produces a pressure profile consisting of two zones (Figure 2). The first zone produces the high pressure commonly associated with a compaction wheel. The second zone provides a long period with far less pressure. The length and the pressure in the second zone could be changed thru minor manual adjustments to the band supports. The common values for the second zone are 25 millimeters long with 210 kPa (30 psi) pressure.

While dramatically increasing the compaction time, the recirculating band also poses several problems. The most significant problem is the thermoplastic tow's tendency to adhere to the band rather then the substrate. Other problems include tow position control, unacceptable shape limitations, and possible thermal oxidation degradation.

The bands are butt welded strips of 130 micrometers by 13 millimeter (5 by 500 mil) high strength stainless steel. In the initial configuration, the band was mounted around three wheels: a compaction wheel and two guide wheels. The compaction wheel is 11 millimeters wide and 25 millimeters in diameter. The other two wheels are wider then the band and grooved to assist guiding the band. One guide wheel is mounted on mechanical springs to allow for compliant compaction pressure. Adjusting these springs changes the tension in the band and the distribution of pressures in the two zones of the compaction area. Although adjustable, the length of the second zone has been kept at approximately 25 millimeters.

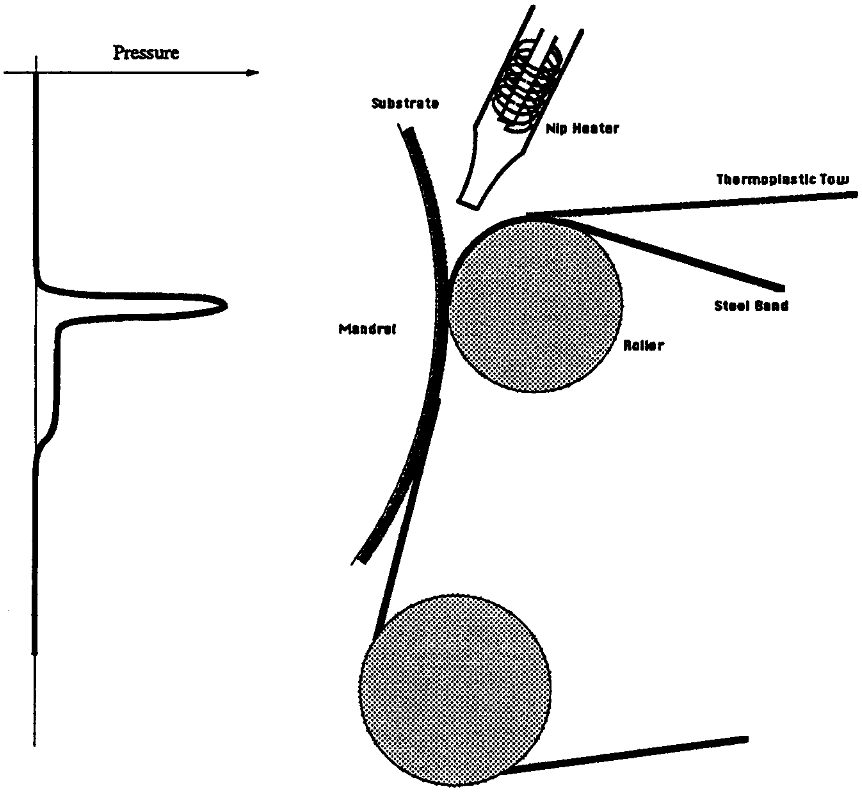


Figure 2. Recirculating Band and Pressure Profile

The compaction wheel is not as wide as the compaction band in order to keep the wheel from contacting the substrate. The compaction wheel is also far smaller then the manufacturer's recommended minimum bending radius for the band. The reduced size decreases the PEEK's viscosity by increasing the strain rate.

The most significant problem with the bands has been the sticking of the material to the band. Intuitively, a composite tow will split across its thickness when pulled from opposite sides while the matrix material is not crystallized. The matrix material will separate where the material more easily flows, that is, the region of least viscosity. According to equation (5) the matrix material's viscosity decreases with increased temperature. In addition, thermal conductivity along the carbon fiber axis is about an order-of-magnitude greater than the conductivity across the fibers. Thus, when contact distances are long, it becomes possible for the temperature of the substrate to be hotter immediately beneath the surface than on the substrate's surface. When this condition exists at the point of the substrate and band separation, the tow will stick to the band.

Based on this theory, either cooling the entire substrate under the band to the glass transition temperature, or maintaining the band at a temperature higher than the substrate, is required to avoid band sticking. If the band is cooled, the duration of the cooling must be sufficiently long, that no combination of substrate fiber orientation, surface geometries, nor laydown rates could preclude the necessary cooling. Experiments showed that maintaining all conditions necessary for adequate cooling is very difficult and not predictable. Given the desired variations of substrates, it is simpler to maintain a high temperature than to ensure adequate cooling. Therefore, the solution was to heat both the nip and the separation points of the band.

Heating the band has some potential problems. With a hot band, a coating of PEEK forms on the outer surface of the band. It is believed that this material is deposited on the substrate during subsequent revolutions of the band as new material is picked up. If the band temperature rises above PEEK's oxidation degradation temperature for an extended time, the oxidized coating on the band may be deposited during subsequent revolutions, contaminating the substrate.

The device described above uses band tension to produce the compaction forces. As a result, the device is only usable on convex surfaces and its effectiveness varies with the surface curvature. To extend the technique to more complex geometries, the band must be pushed onto the surface along the contact region. A newer version of the laydown head, shown in Figure 3, uses a set of spring loaded rods to provide the necessary pressure. With these rods, the head can be used on surfaces with less regard for the surface curvature.

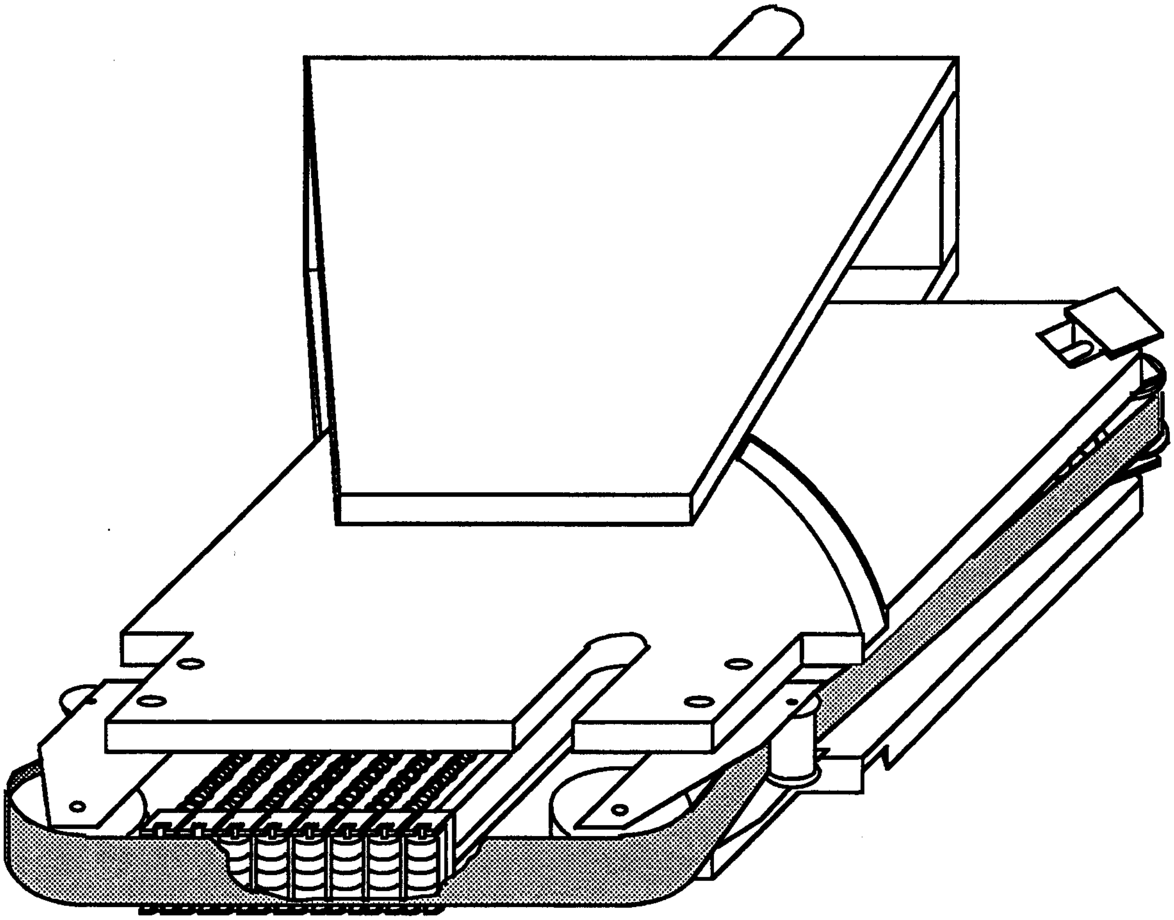


Figure 3. Improved Band Roller

Concave surfaces pose additional problems for the heating system. When the compaction surface is pressed into a concavity, the compaction device shields the nip and the immediate surrounding area from the heater's discharge. Therefore, the air jet must be directed at points on the substrate and the incoming tow prior to the nip. The temperature of the substrate and tow at these points must be increased so that heat losses in the shielded region do not lower the temperature of the substrate or tow surfaces below the thermoplastic processing temperature until after the nip.

Finite Element Modeling of the laminate indicates that the substrate may be heated high enough to provide the necessary temperature in the nip. Figure 4 shows the heat distribution in a cylindrical part form generated by prolonged heating. The figure shows the band temperature remains above melt well beyond the heating point. The figure also shows that the substrate exceeds the melt temperature to a depth of about six plies.

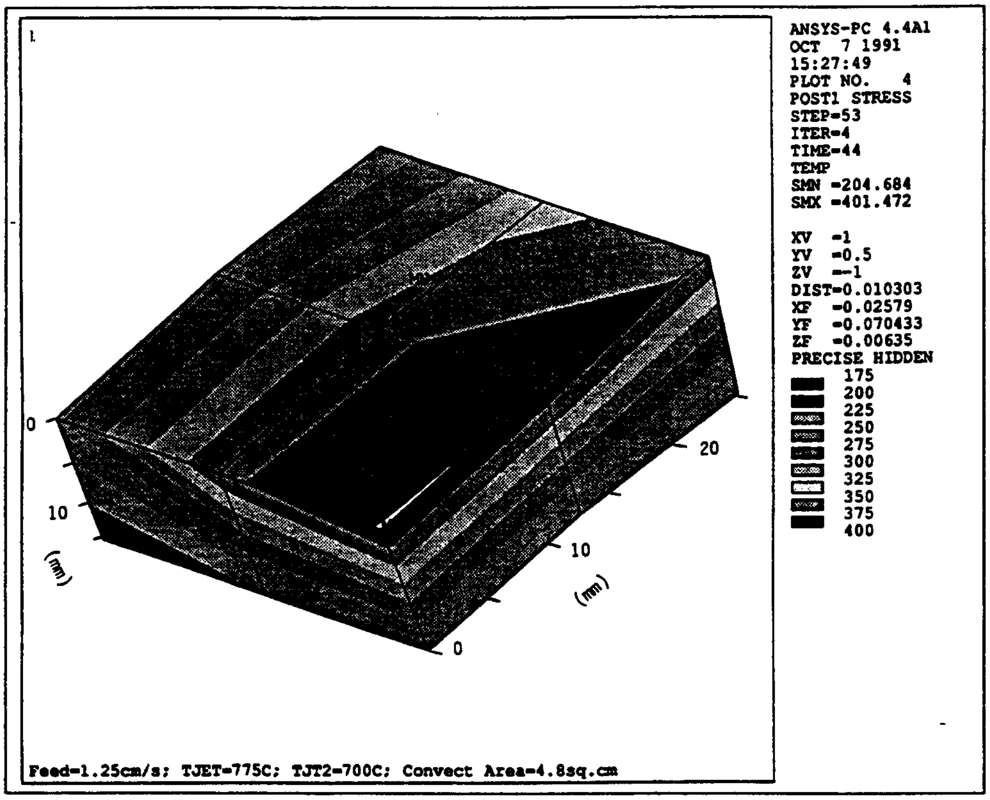


Figure 4. Heat Distribution in Cylindrical Part.

Like other aspects of compacting the thermoplastic, this deep melting has both advantages and disadvantages. The application of pressure to the remelted thermoplastic increases the Compaction Number by increasing the time. The deep melting also results in unacceptable crystal growth when cooling is unassisted. For now, the crystallinity problem is being considered separate from the compaction problem.

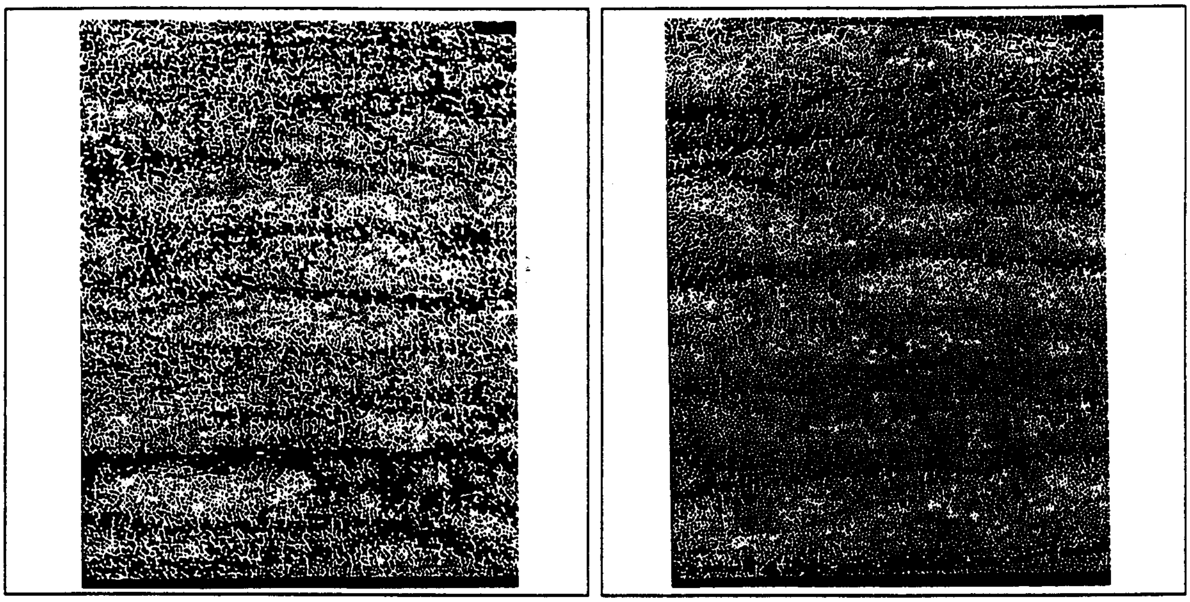
The use of a thin steel band also generates problems with tow position control. Since the band recirculates, it is repeatedly heated and cooled as it approaches the nip and leaves the substrate. As the metal expands and contracts with the thermal cycling, the band may become distorted. A distorted band will not roll true and may drive the tow towards the side. Steering corrections are then required to keep the tow properly aligned. Fortunately, this problem is minor at laydown rates of less then 50 millimeters per second. Above this rate the tow may be steered through minor adjusts to the yaw of the compaction head. Automating this solution has been left for future efforts.

Results

Since the process refinement has been very dynamic, the results to this point are more qualitative then quantitative. The preferred method of evaluation has been photo-micrographs. Digital image analysis has also been used to determine the void and fiber content of some samples. The photo-micrographs have shown a general improvement in the consolidation and has supported various aspects of the general theory.

As stated in the previous section, deep heating causes unacceptably slow cooling of the substrate. Slow cooling rates cause excessive crystal growth in the thermoplastic matrix. Since the level of crystallinity effects the density of the material, density based measurements are not indicative of the level of compaction achieved. Thus, we have relied on photo-micrographs to monitor progress.

The two photos in Figure 5 are photo-micrographs of two samples produced using different laydown heads.



a. Compaction Wheel Sample b. Band and Wheel Sample

Figure 5. Sample PhotoMicrographs.

Figure 5a was produced using a lone compaction wheel. Figure 5b was produced by the wheel and band system. Image analysis of the wheel and band sample shows a void content of less then one percent in the inner plies. The inner plies of Figure 5b also show fewer voids than the outer most layers. This demonstrates the effect of reprocessing which is experienced by the early layers.

Conclusion

Thermoplastic composites offer the opportunity to more cost effectively manufacture composite parts by consolidating the thermoplastic material during the initial layup and by avoiding several manufacturing steps. The in-situ consolidation is dependent on achieving adequate compaction.

Based on experimental results and fluid flow theory, Georgia Tech proposes a dimensionless Compaction Number (equation 1). Further experiments indicate that the expression is a fair predictor of compaction in in-situ consolidation systems. The equation also indicates that increasing the compaction time or decreasing the viscosity by increasing the processing temperature or increasing the strain rate would improve the compaction in those systems.

Extending the compaction time is the current approach used at the AMRF's Composite Workstation. The addition of a recirculation steel band increases the compaction area which increases the compaction time without a laydown rate reduction.

The band presents several potential problems, such as sticking and reduced position control. Although troublesome, these problems are manageable. Maintenance of an appropriate temperature profile in the substrate can be used to alleviate the sticking and minor adjustments to the compaction head yaw angle solves the tow control problem.

Results with the band have been qualitative to this point, but are promising. Other aspects of consolidation must be considered before quantitative results may be compared to the efforts of others. Most importantly, the recirculating band may be readily designed into a compact head. Thus, the requirements for the workstation's fiber placement are fulfilled.

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