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Free Form Fabrication of Thermoplastic Composites

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Free Form Fabrication of Thermoplastic Composites

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Abstract

This report describes the results of composites fabrication research sponsored by the Laboratory Directed Research and Development (LDRD) program at Sandia National Laboratories. We have developed, prototyped, and demonstrated the feasibility of a novel robotic technique for rapid fabrication of composite structures. Its chief innovation is that, unlike all other available fabrication methods, it does not require a mold. Instead, the structure is built patch by patch, using a rapidly reconfigurable forming surface, and a robot to position the evolving part. Both of these components are programmable, so only the control software needs to be changed to produce a new shape. Hence it should be possible to automatically program the system to produce a shape directly from an electronic model of it. It is therefore likely that the method will enable faster and less expensive fabrication of composites.

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1 Introduction and Motivations

Available methods of forming structures of continuous-fiber polymer-matrix composites (hereafter, "CFPM composites") all require mandrels, forms, or dies. Such forms place constraints on the producible shapes. For example, filament winding on a mandrel cannot produce concave objects, and the requirement that the mandrel be removed from the interior of the finished structure makes very difficult the fabrication of shapes having a wider cross-section in the middle than at the ends. The need for mandrels, molds, dies, or forms adds expense to the cost of fabricating a new shape, particularly if only a few copies of the shape are desired.

In contrast to this state of affairs, other materials can be fabricated into complex shapes by various methods of rapid prototyping. These technologies are characterized by the ability to produce shapes of very high complexity directly from an electronic model of the shape, without needing a new form to be made. An example is stereolithography, in which the shape is built up layer by layer, using a computer-controlled laser to selectively cure epoxy resin. To produce a new shape, only the software controlling the curing is changed; no changes to the hardware are necessary. However, stereolithography can only build structures composed of pure resin, or resin containing chopped (non-continuous) fiber. Another example of rapid prototyping is laser sintering; in this technique, the laser energy bonds powdered metal and/or ceramic. Given the success of these technologies, it is natural to seek a method of rapid prototyping for CFPM composites, so that the domain of rapid prototyping is extended to these high-modulus, low-weight materials. Such a method would be able to produce shapes of high complexity, not subject to the shape constraints imposed by the need for molds; furthermore, the only change to the system needed to produce a new shape would be to the software, which would be automatically generated from an electronic model of the shape. Such a method would have the dual advantages of being able to produce shapes currently producible only with great difficulty, and at lower cost since mandrels need not be made.

We have developed a method of producing structures composed of CFPM composites that does not require a mandrel, and is therefore not subject to these constraints on producible shapes. This allows shapes to be produced that are difficult to make by existing methods. For example, a cylinder-like object, with a square cross-section in the middle and circular cross-section at the ends, can be made with our method, but filament winding would require a destructively removable mandrel. Furthermore, the method is implemented with programmable devices, allowing automatic programming of the system to produce a shape from an electronic model of it. The method is the basis of a CFPM rapid prototyping system as envisioned in the previous paragraph.

We have demonstrated that our method has the capability to:

1. Produce composite parts of the desired shape under automatic control (to date, we have produced right circular cylinders of various thicknesses);

2. Produce satisfactorily consolidated composites using preconsolidated thermoplastic resin with graphite or Kevlar fibers;

3. Produce satisfactory parts of significant thickness (to date, up to 1/8th of an inch).

The quality of the parts we have produced is comparable to that of parts produced using filament winding on a mandrel.

The remainder of this paper is divided into two major sections: a summary of existing fabrication methods; and a description of our system. The conclusion describes our on-going work.

2 Fabrication Methods for Composites

Fabrication methods for composite structures fall into six basic categories: layup, resin transfer molding, filament winding, fiber placement, pultrusion, and braiding/weaving. We describe each in turn. The boundaries between methods are often fuzzy, as the reader will observe. More complete descriptions are available elsewhere, for example, [3].

2.1 Background and Terminology

A composite material, as its name implies, consists of two or more distinct materials. The composite exhibits the best properties of the constituent materials. Well-known examples are bricks made of mud and straw, and structures made of concrete and reinforcing bars. Composites of ceramic and metal have recently become available.

The composites of interest in this work consist of a high-modulus fiber and a polymer binder. The non-fibrous material is called the *matrix*; examples are polymers such as epoxy resins and thermoplastics such as nylon. The types of matrix are subdivided into *thermosets* and *thermoplastics*. Thermosetting materials are chemically and irreversibly altered during the cure process, which often involves the application of heat (in some cases, the heat is the exotherm of the curing reaction). Thermoplastics simply melt when heated; they may be remelted a number of times, though they degrade after a number of heating/cooling cycles.

These materials are available in a number of forms. The fiber may be separate from the matrix material, or it may be already impregnated with it. The latter form is called *prepreg*. Thermoplastics, which are solid at room temperature, may be *commingled*, or woven, with the fibers, or *preconsolidated*, where they are already melted together with the fiber. Preconsolidated and prepreg materials are often sold as rolls of flat tape.

2.2 Layup

In this process, fiber and matrix material are placed in a mold. The fiber and matrix may be applied separately or simultaneously. Once the placement is complete, the resin is cured. This can be at room temperature and pressure, but better results are obtained when both quantities are elevated in an autoclave or press.

In hand layup, fiber mats are placed, resin is sprayed or painted on, and is pressed into the fiber with rollers or squegees. Then the material cures at room temperature.

Fiber and resin can be combined before layup in several ways. In spray layup, fiber is cut and combined with resin in a spray gun, which is then used to coat the mold. Prepreg materials can also be used; when they are, automated layup becomes easier, in the form of automatic tape layup. The system described by Olsen and Craig ([7]) consists of a robot mounted prepreg tape dispenser. This dispensing head is capable of cutting the tape, restarting the dispensing process, and applying pressure at the point of application. It differs from filament winding in this ability to stop dispensing tape (by cutting) and restart at a different point.

2.3 Resin Transfer Molding

The hallmark of resin-transfer molding (RTM) is the injection of matrix resin into a closed mold which contains the fiber. Curing takes place in the mold. The fiber can be woven or braided into an approximation of the final shape, or preform, before being placed into the mold.

2.4 Filament Winding

Filament winding can produce very large shapes, provided that the curvature is everywhere positive. A filament winding machine consists of a rotating mandrel and a fiber dispensing head that travels the length of the mandrel. Synchronized with the mandrel rotation, the head can change the angle of the fiber with respect to the mandrel axis, so that helical plies optimized to handle expected loads can be laid down.

These machines are programmable, so that different winding patterns can be specified. The mandrel can also be changed, allowing even more flexibility.

The three main constraints imposed by the filament winding process, in order of increasing difficulty to overcome, are:

1. The mandrel must be removed from the interior of the complete structure.
2. The object must have positive curvature everywhere.
3. The mandrel must be fabricated. If the shape does not allow the mandrel to be removed intact (e.g., a tube with wider diameter in the middle than at the ends), it can be removed destructively. Plaster and salt mandrels have been used for this purpose.

An object with reentrant curvature can be filament wound, if the winding is followed by suitable postprocessing, such as hand layup. But the requirement for a mandrel cannot be avoided.

2.5 Fiber Placement

This technique was described above. It is an improvement on filament winding in that it can produce shapes with reentrant curvature. However, it still requires a mandrel, and

therefore retains the associated disadvantages. Furthermore, the cost of fiber placement machines is very high.

2.6 Pultrusion

Pultrusion is the most economical fabrication method for objects having constant cross-section. The fiber and uncured resin are pulled through a heated die which simultaneously shapes and cures the product. Beams and driveshafts are examples of products well-suited to this process.

Note that while this process does not require a mold, a die of the cross-sectional shape is needed.

2.7 Braiding and Weaving

This technique was mentioned in the discussion of RTM. Dry fibers are braided or woven into configurations optimized for the expected load, and approximately the shape of the target. The resulting network is placed in a mold, impregnated with resin, and cured. The braiding and weaving is done by programmable machines.

Cost savings of up to 50% have been observed compared to filament winding. A wide range of shapes can be produced with the same equipment, and smooth transitions from one shape to another are possible. A mold is still required for resin impregnation and curing.

3 System Description

Our system consists of two main components. The first is a reconfigurable forming surface on which heat and pressure are applied to the composite material. This is used to mold and cure each patch of the final shape. The second component is a 6 DOF robot arm, whose role is to position the evolving structure so that the patch currently being molded is held at the proper pose. Both the forming apparatus and the robot are controlled by a single controller. Figure 1 is an overall view of the system.

The attachment of the robot to the part is surprisingly simple. The arm simply grasps the part holding fixture. The part-holding fixture can be any piece of material attached directly to the part being made. The attachment is made by inserting the part-holding fixture into the forming system along with the composite material, so that the first patch is fused directly to the fixture. The cross-section of the portion of the part fused to the fixture is cut off when the part is complete (similar to a sprue in molding). Because the shape of the patch and the location and orientation of the robot relative to the formed patch are continuously variable, very few limitations exist on the shape of the part that can be produced.

The original system used a Fanuc RJ controller and S-800 arm. Both commingled and preconsolidated composites of thermoplastic resin and continuous fiber material have been successfully formed with this apparatus. We have since implemented it with a Stäubli arm and Adept MV controller.

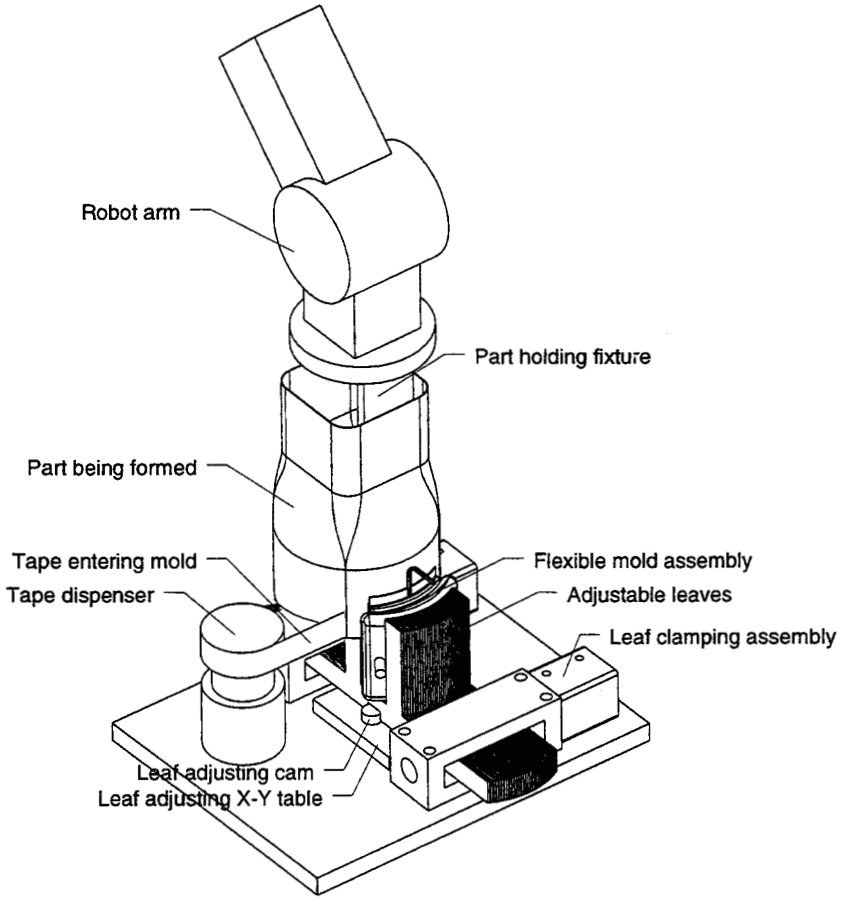

Figure 1: Overall view of agile composite forming apparatus

We now describe the form and function of this forming system, then how it is integrated with the robot. Figure 2 shows a cross section of the original forming apparatus. The mold is shaped by a number of adjustable leaves that act like a contour gauge. By adjusting the position of the leaves, a large class of continuous two-dimensional curves can be realized. In the original system, the total length of the forming surface composed of the edges of the leaves is about two inches. The required patch shape is made by the leaf-adjusting cam, which runs through the slot on the bottom of the apparatus. The cam is driven by an X-Y table, commanded to move in a series of paths that result in the required shape. The commands to the X-Y table are sent from the controller to the X-Y motors on a serial line. Once the leaves are in the proper position, the clamping assembly is actuated to hold the leaves in place during the forming process. The patch is then molded and cured by applying heat and pressure to the portion of the part between the leaves.

Pressure is applied by inflating the silicone rubber bladder (on the right in figure 2), and heat is applied by the flexible heater that is folded so that both sides of the part are heated. A thermocouple on the back side of the heater is used as input to the temperature control system, which is implemented in the robot controller.

In the original forming apparatus, Teflon was used as the separator between the composite and the heater, and also served as the mold release. Alumina felt insulates the heated

section from the forming leaves. It also smooths out the stair-stepping that the leaves introduce. The new forming apparatus replaces the Teflon with spring steel shim stock, 0.002 to 0.005 inches thick. Using this results in a surface finish as smooth as any structure made on a metal mandrel.

Other changes in the new forming apparatus include:

1. It is now six inches tall, instead of two inches;
2. There are only 16 leaves, instead of 32;
3. The space taken by the 16 leaves left out is now HDPE and Teflon to ensure that the leaves slide easily when they are set to a new configuration;
4. The leaves are made of stainless steel instead of aluminum, so heat conduction losses are reduced sufficiently to eliminate the need for the alumina insulator;
5. We use separate heaters, one on each side, separately controlled.

We now comment on why these changes were made.

The height is greater to allow a greater reach into the evolving structure. The original apparatus only allowed us to cure patches at the very edge of the structure. Since the heat and pressure are applied at the ends of the leaves, we can reach four inches into the structure. This is related to the need to make structures having multiple fiber directions, which is discussed in section 5.

We use only sixteen leaves because the spring steel used as the molding surface is sufficiently stiff to maintain its shape when supported at regular intervals. Filling these gaps with low-friction plastics eliminates sticking problems when resetting the shape of the leaves.

Finally, we needed to use alumina felt as an insulator between the flexible heater and the leaves in the previous apparatus, because the aluminum leaves were conducting away too much heat. The felt would compress with repeated curing cycles, leading to positional errors. Stainless steel conducts heat at only 6% of the rate of aluminum, eliminating the need for the alumina felt. Using separately controlled heaters on each side of the heated patch gives more even heating. In the original apparatus, there was a pronounced thermal gradient across the heated patch, due to one side being in contact with a very good thermal insulator (the bladder), and the other in contact with an inferior thermal insulator (stainless steel). Yet the single control provided the same power to both sides.

Next, we describe system control. Figure 3 is a control schematic.

The following control cycle is executed repeatedly until the shape is complete. Initially, the heater is off, the bladder is vented, and the clamps are not set.

1. Configure the forming surface, and clamp.
2. Move robot arm so that the next patch to form is at the correct pose.
3. Inflate bladder and turn on heater.

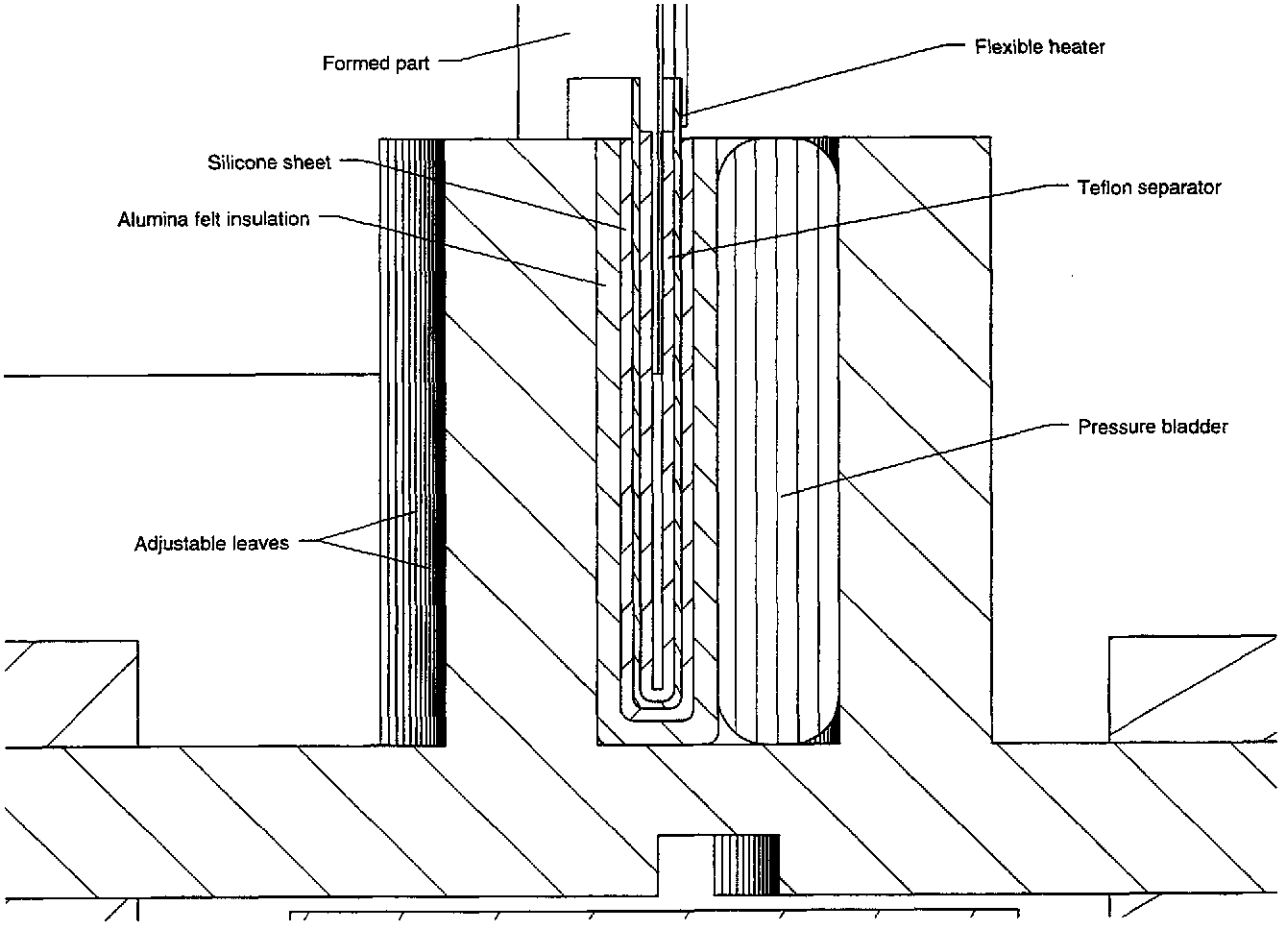

Figure 2: Cross section of forming apparatus

4. When heater reaches material melt temperature, maintain for specified time, then switch off.

5. When heater reaches material consolidation temperature, vent bladder.

Results of a study on how pressure and dwell time at melt temperature affect the quality of the completed part are given in Section 6.

4 An Example

This section describes how the system is programmed to produce a right circular cylinder. The winding pattern required to realize the desired shape must be specified. A helix having radius a and pitch c is taken as this winding pattern; c is chosen to provide the right amount

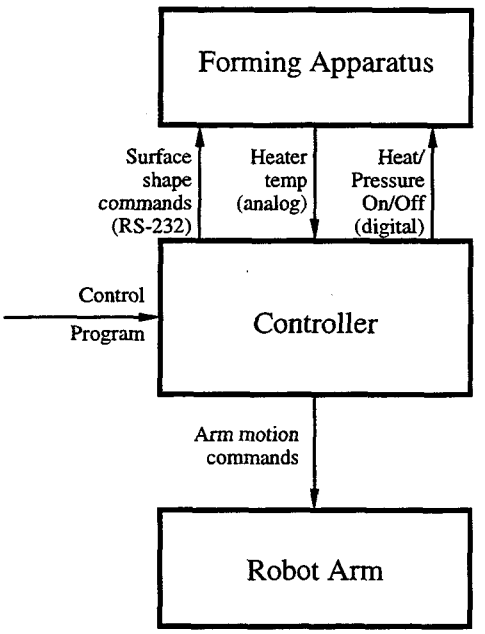

Figure 3: System block diagram

of overlap on successive wraps. The parametric representation of the helix is:

$$a\cos(s/w)\mathbf{i} + a\sin(s/w)\mathbf{j} - c(s/w)\mathbf{k},$$

where $w = \sqrt{a^2 + c^2}$; s/w serves as the arc length parameter for the cylinder. Arc length corresponds directly to the amount of composite material paid out in forming the cylinder. That is, the number of steps of the forming process stands in for the arc length of the winding pattern.

For each step, we must determine the shape of the forming surface and the pose of the robot which holds the structure built so far. For the cylinder, the forming surface shape is not changed; it is the arc of a circle of the desired radius. The pose of the robot traces out the helix given as the winding pattern. The pose at each step is easily determined, as follows.

For space curves satisfying certain continuity, differentiability, and curvature conditions, such as the helix, there is a unique set of three mutually orthogonal unit vectors at each point on the curve ([5]). These vectors are called the unit trihedron of the curve at the given point, and serve as the specification of the orientation of the robot for that step of the process. The unit trihedron consists of the *unit tangent* vector, the *unit principal normal* vector, and the *unit binormal* vector. Let $\mathbf{r}(s)$ be the position vector of the curve; then

$\dot{\mathbf{r}}(s)$ is the tangent vector (the dot indicates differentiation with respect to the parameter s). If the parameter is the arc length, then the tangent vector is guaranteed to be of unit magnitude. We denote the unit tangent vector by the symbol $\mathbf{u}(s)$; like the other members of the unit trihedron, its value is functionally dependent on the parameter.

The principal normal is defined as $\ddot{\mathbf{r}}(s)$; its magnitude is defined to be the curvature of the curve. Therefore, the unit principal normal is obtained from the principal normal by dividing it by the curvature at that point (which cannot be zero). The unit principal normal vector is denoted by $\mathbf{p}(s)$.

The unit binormal $\mathbf{b}(s)$ is defined as

$$\mathbf{b}(s) = \mathbf{u}(s) \times \mathbf{p}(s).$$

The procedure used to obtain a program to trace the helix is to compute the unit trihedron as a function of the arc length, and use it to determine the required pose for each step of the forming process. The unit trihedron is represented as a rotation matrix. The Fanuc R-J controller requires that poses be specified as yaw-pitch-roll triples, so we had to take the further step of extracting these values from the rotation matrix. The procedure given on page 47 of [2] can be used for this.

In particular, the helix required for the coordinate system used in our workcell is given parametrically as

$$\mathbf{r}(s) = -a\cos(s/w)\mathbf{i} - a\sin(s/w)\mathbf{j} - c(s/w)\mathbf{k},$$

leading to the rotation matrix

$$\begin{pmatrix} \cos(s/w) & \sin(s/w) & 0 \\ (a/w)\sin(s/w) & -(a/w)\cos(s/w) & -c/w \\ (c/w)\sin(s/w) & -(c/w)\cos(s/w) & -a/w \end{pmatrix}.$$

The first row is $\mathbf{p}(s)$, the second is $\mathbf{u}(s)$, and the third is $\mathbf{b}(s)$. Then, when the parameter is zero, the first row projected onto the xy plane is parallel to the x axis, and the second row projected onto the xy plane is parallel to the y axis.

Finally, the yaw-pitch-roll angles required are extracted using the following formulas (where $\beta = [((a/w)\sin(s/w))^2 + (\cos(s/w))^2]^{1/2}$):

$$\text{yaw} = \text{atan2}\left(\frac{-(c/w)\cos(s/w)}{\beta}, \frac{-(a/w)}{\beta}\right),$$

$$\text{pitch} = \text{atan2}\left(\frac{-(c/w)\sin(s/w)}{\beta}, \beta\right),$$

and

$$\text{roll} = \text{atan2}\left(\frac{(a/w)\sin(s/w)}{\beta}, \frac{\cos(s/w)}{\beta}\right).$$

The right circular cylinder illustrated here affords a simple closed form solution. In general, complex parts will be produced using an identical analysis but employing numerical solutions of the equations.

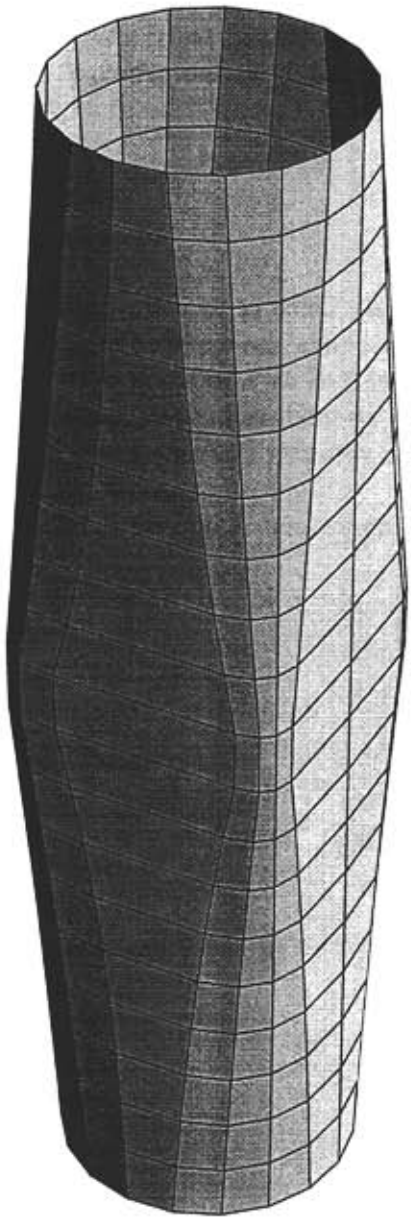

Figure 4: Superquadric cylinder

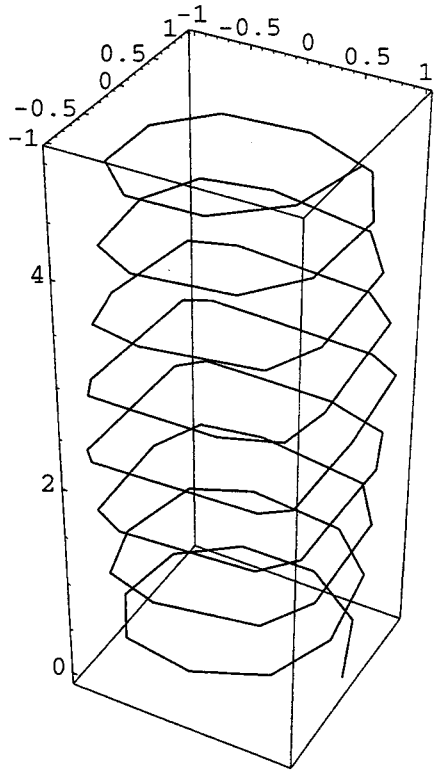

Figure 5: Winding pattern for superquadric cylinder

This analysis also requires that the function $\mathbf{r}$ have derivatives. This is not always the case, of course. For example, the shape shown in figure 4 is specifed as a superquadric surface, and a winding pattern — the function $\mathbf{r}$ — appropriate for it is also a superquadric, namely

$$\mathbf{r}(s) = \cos(s)^{1/5+(s/2\pi-4)/5}\mathbf{i} + \sin(s)^{1/5+(s/2\pi-4)/5}\mathbf{j}$$

(see figure 5). Because the powers are between 0 and 1, the winding pattern has no derivative. Furthermore, the arc length of such a curve is generally not expressible in closed form (for, as is well known, the arc length of a simple ellipse cannot be expressed in closed form), so an arc length parameter cannot be given in closed form.

5 Multiple Fiber Directions

As discussed above, a complex part can be developed using a continuous piece of tape as the raw composite material. However, this results in the structure having only one direction of fiber, which is almost always unacceptable because part strength is so highly anisotropic. Four fiber directions are usually considered to be minimally acceptable. Furthermore, the requirement for a continuous winding pattern adds some constraints to the forming process.

For example, parts that are not tubular in shape, such as aircraft panels, must be formed in mating pairs or by cutting and restarting the tape at the edge of the panel. In addition, for many shapes with sharp variations in contours, such as in areas around bosses, the need for a continuous winding pattern severely limits the forming sequence. Also, parts containing branches are not directly conducive to continuous winding patterns. For these reasons, a second and more general forming technique has been developed. The technique uses the same forming apparatus as the continuous tape system but feeds the composite material in a single multidirectional patch at a time. These patches are premade, and each has four fiber directions. In operation, the patch is somewhat larger than the heated area of the form, and one patch is fed into the form during each forming operation. With patchwise forming, the sequence of building the part is limited only by the mechanics of the forming system and the difficult mathematical or numerical analysis of the winding path is not required. The only requirement is the determination of the form shape for any given patch. This can be obtained from solid-modelling systems when the desired surface is expressed as a function of two parameters. Further, the use of patchwise feeding is more conducive to production of multi-directional fiber parts. While multi-directional fiber tape is usable in the continuous tape system, there are limitations as to the direction in which the tape can be added to the part due to the constraint of the winding path. For patch feeding systems, the fibers can be oriented in any desired direction.

Our patch feeding device consists simply of a commercially available gripper and a long stroke pneumatic cylinder. A patch dispenser feeds the next patch into the pneumatic gripper. The gripper then closes and the long stroke pneumatic cylinder pushes the patch forward into the forming apparatus. This system can be readily automated since it simply requires a supply of uniform size patches to be fed to the patch feeding device.

6 Sectioning Analysis

This section describes a study of the quality of the consolidation obtained with our forming process. Each specimen consisted of eight layers of preconsolidated tape, alternating orientations by 90 degrees with each layer. The object of the study was to determine which combination of pressure and time at the melt temperature of the nylon (450 F) led to the best consolidation and lowest void content. For each specimen, a section of about 2 cm by 1 cm was cut, potted in epoxy, polished, and coated with a thin metal layer. The resulting specimen was then examined with a scanning electron microscope. Five sections were studied, covering the four regimes of: 200 seconds at 6 psi and 10 psi, and 120 seconds at 6 psi and 10 psi. There were two specimens done at 200 s and 10 psi, to determine how the specimens could vary under the same curing conditions.

The first two views of specimen 1 (figures 6 and 7), as in all the succeeding specimens, give an overall view of the specimen. Consolidation is complete throughout the entire thickness (about a sixteenth of an inch). No voids are present; fiber volume fraction is estimated at 55% to 60%; overall quality is considered to be very good.

#1 10°

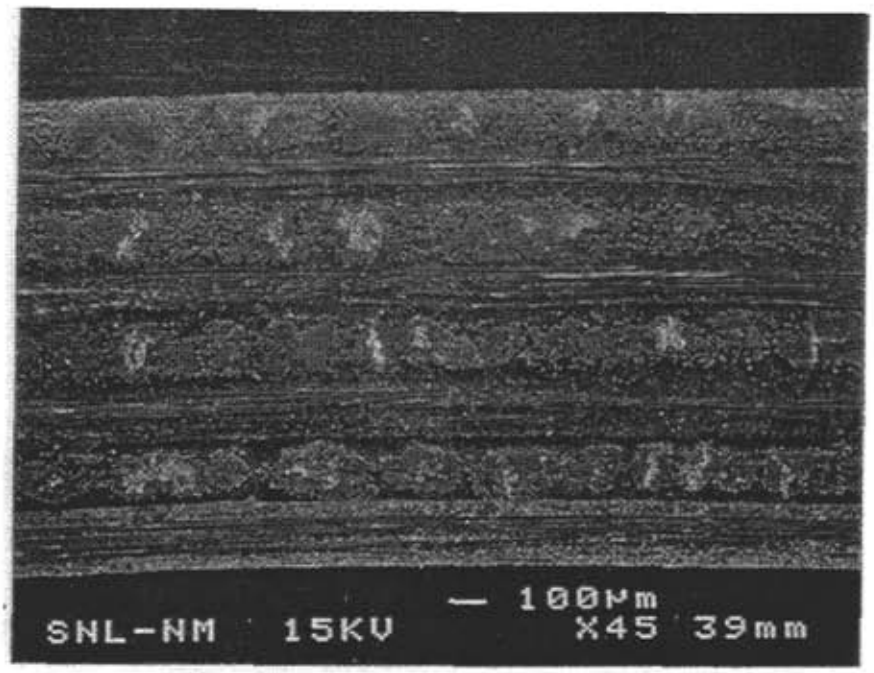

Figure 6: Specimen 1, View 1 (200 s, 6 psi)

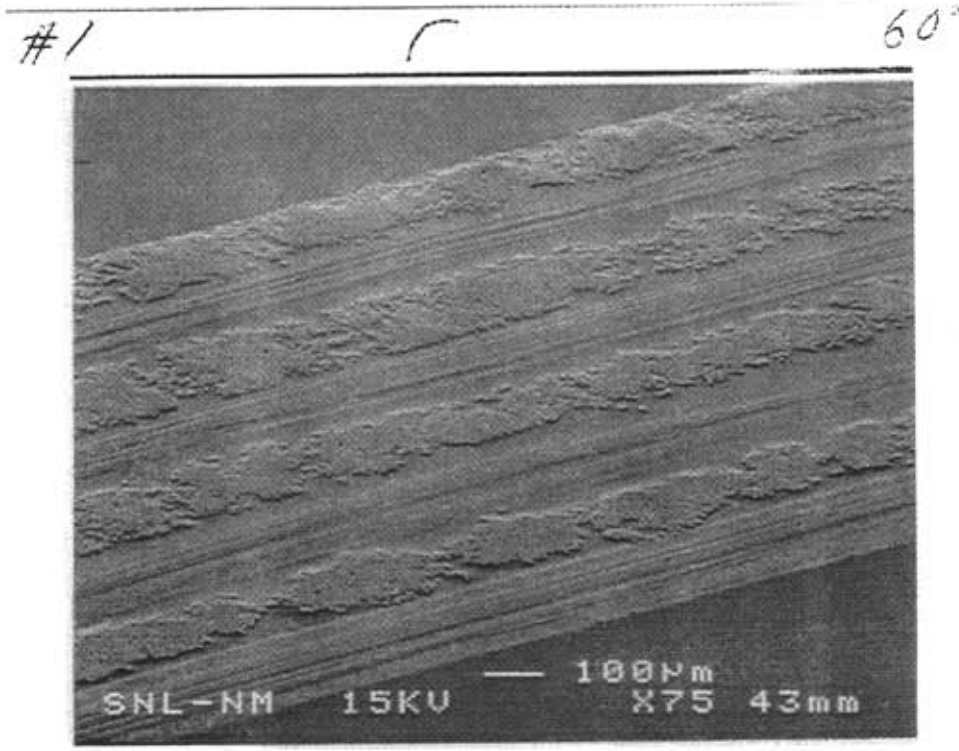

Figure 7: Specimen 1, View 2 (200 s, 6 psi)

The third and fourth views of the first specimen (figures 8 and 9) are closeups of the white areas, which indicated poor adhesion of the nylon matrix to the fiber. The origin of these areas is unknown. Scratches are an artifact of the polishing process.

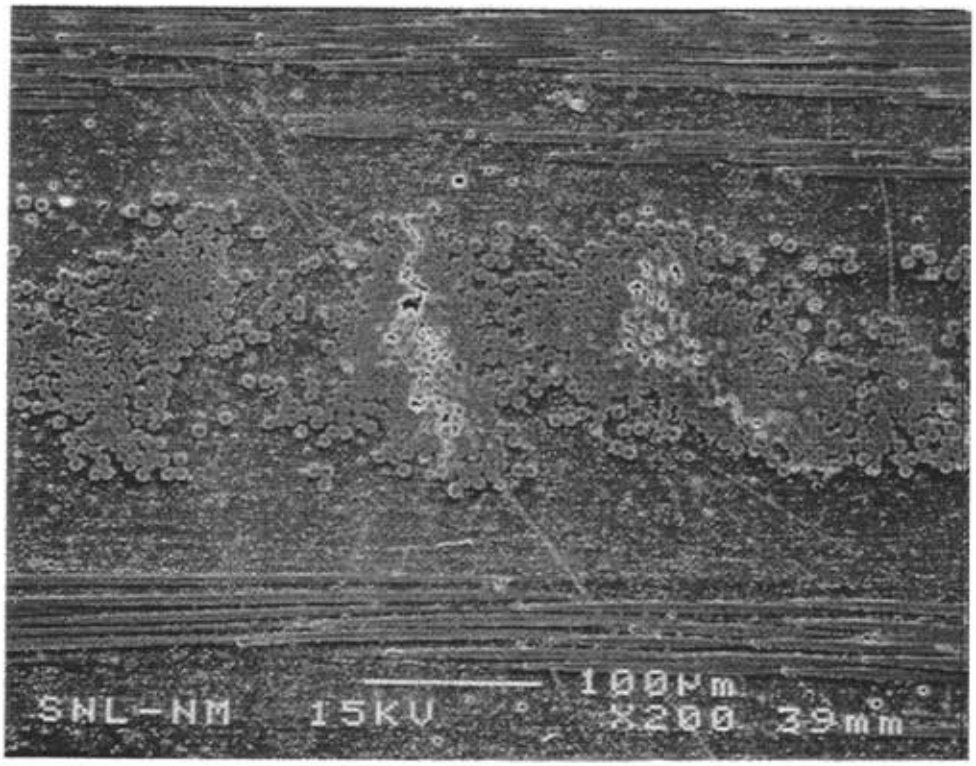

Figure 8: Specimen 1, View 3 (200 s, 6 psi)

#1 10

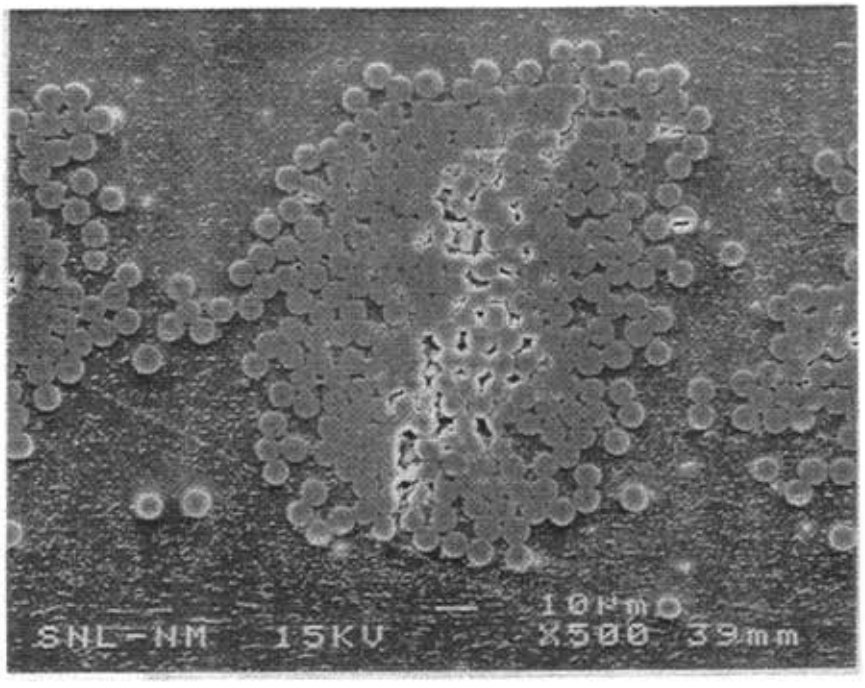

Figure 9: Specimen 1, View 4 (200 s, 6 psi)

Specimens 2 and 3 were cured at 200 seconds and 10 psi. Both show voids; we suspect that the origin of the voids is non-uniformities in the original material, which are often visible to the naked eye. Unfortunately, we did not take data on this before curing the specimens. In both specimens, the voids are near the center of the specimen, indicating that the heat applied from both sides did not heat the center sufficiently flow material into the voids. Other than the voids, consolidation appears good.

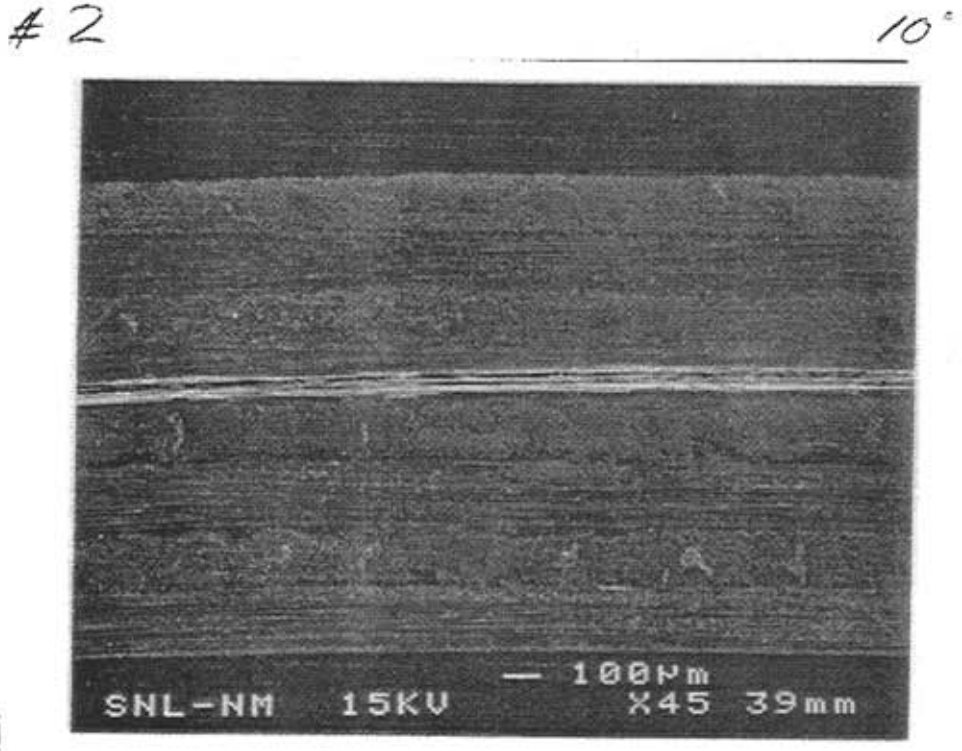

Figure 10: Specimen 2, View 1 (200 s, 10 psi)

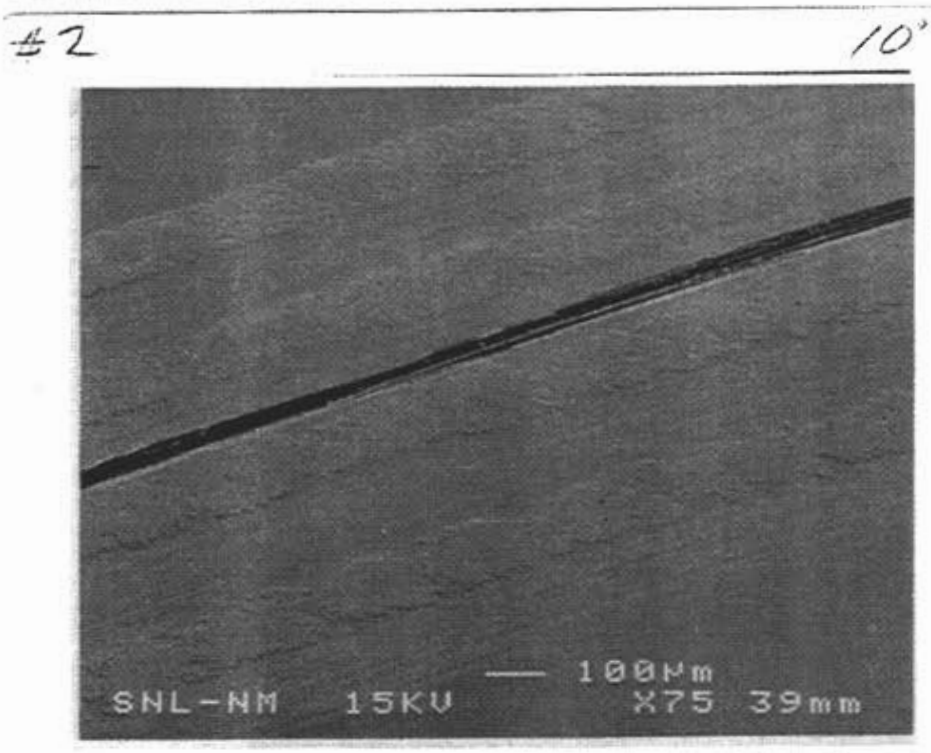

Figure 11: Specimen 2, View 2 (200 s, 10 psi)

#3 10°

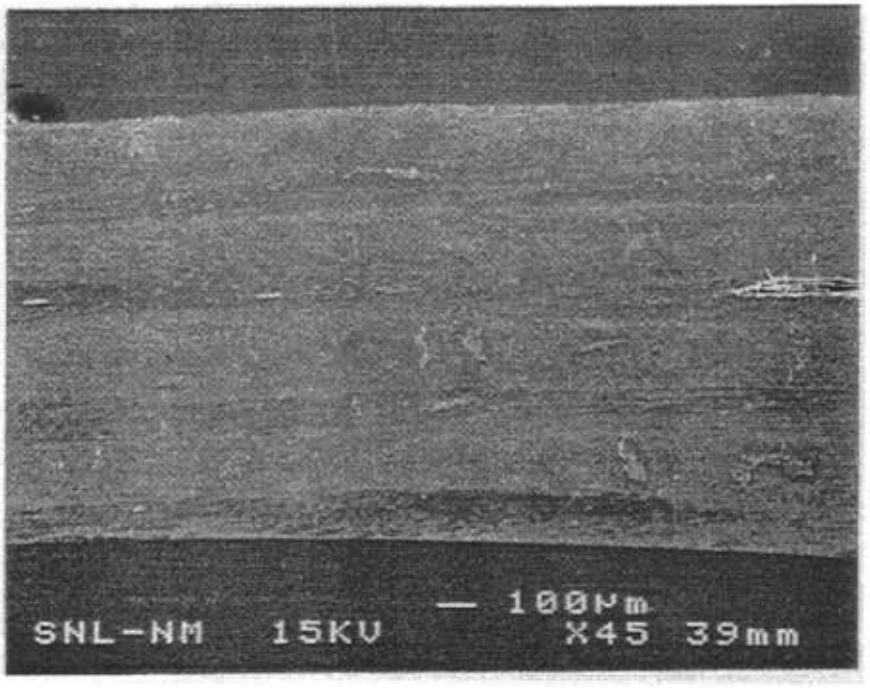

Figure 12: Specimen 3, View 1 (200 s, 10 psi)

#3 60°

Figure 13: Specimen 3, View 2 (200 s, 10 psi)

#3 10"

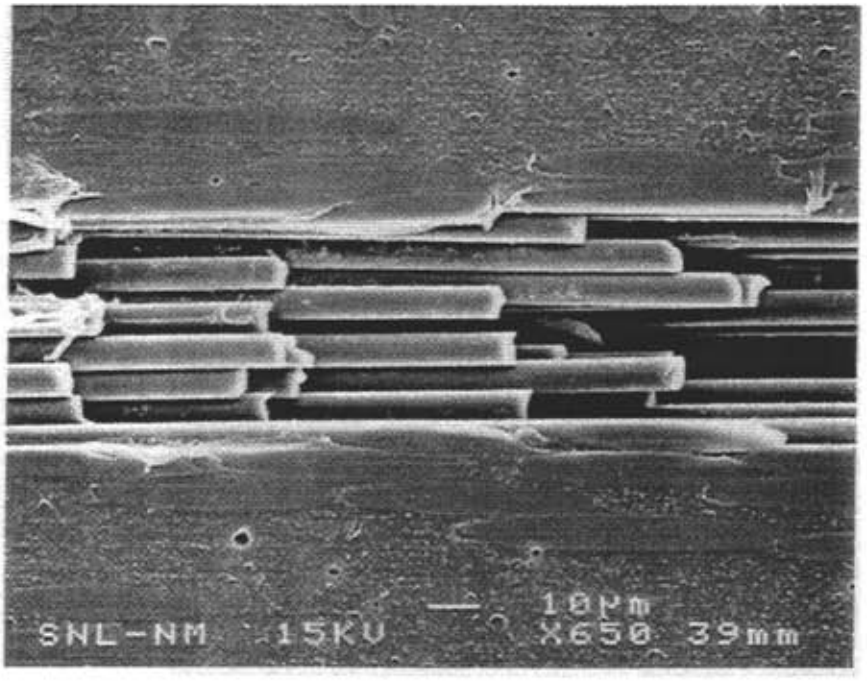

Figure 14: Specimen 3, View 3 (200 s, 10 psi)

#3 10°

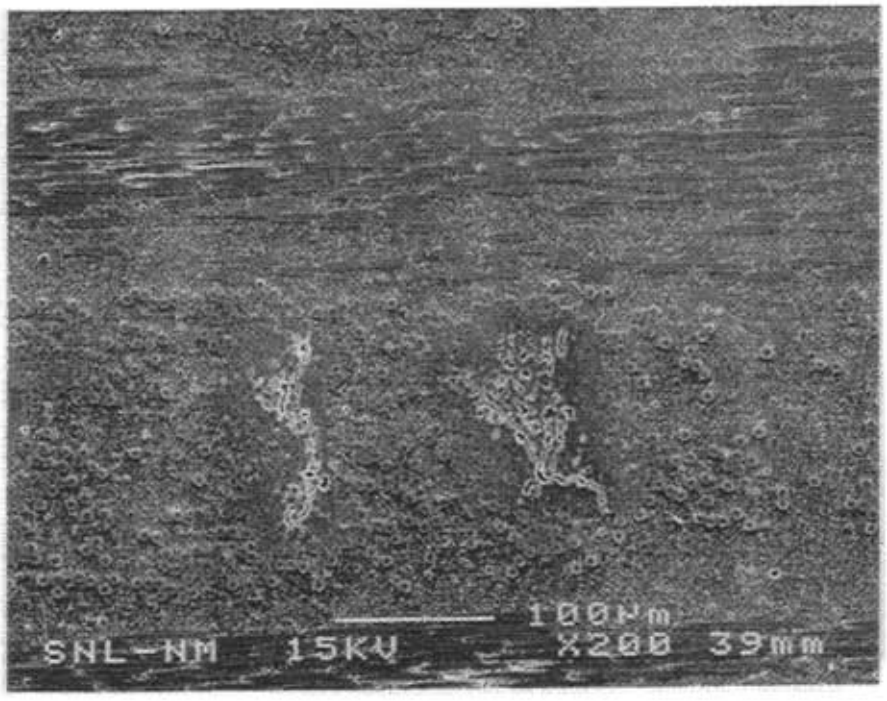

Figure 15: Specimen 3, View 4 (200 s, 10 psi)

Specimen 4 was made at 120 seconds dwell time and 10 psi. A large center void is apparent, larger than those of specimens 2 and 3. This suggests that dwell time at melt temperature is crucial in filling voids.

#4 10"

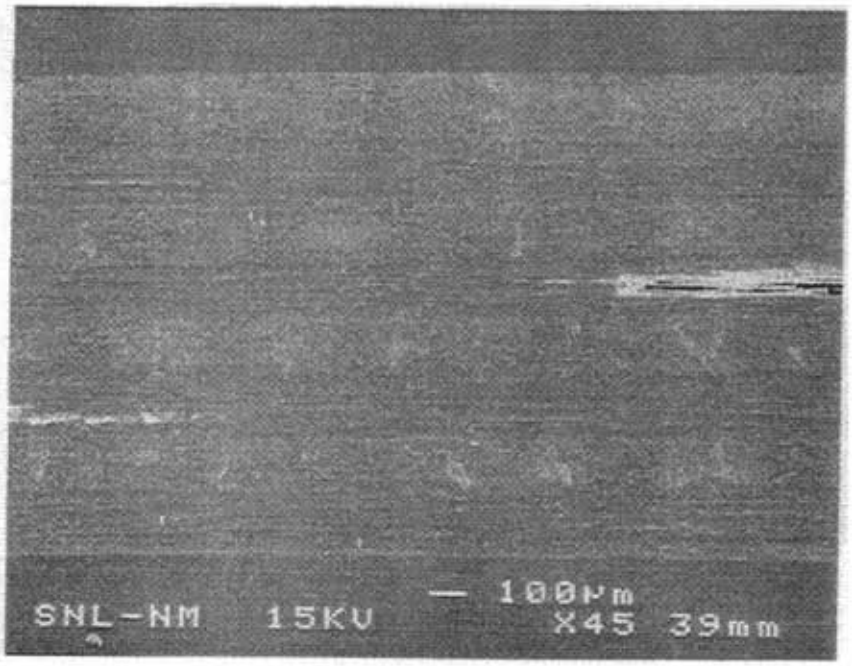

Figure 16: Specimen 4, View 1 (120 s, 10 psi)

#4 60°

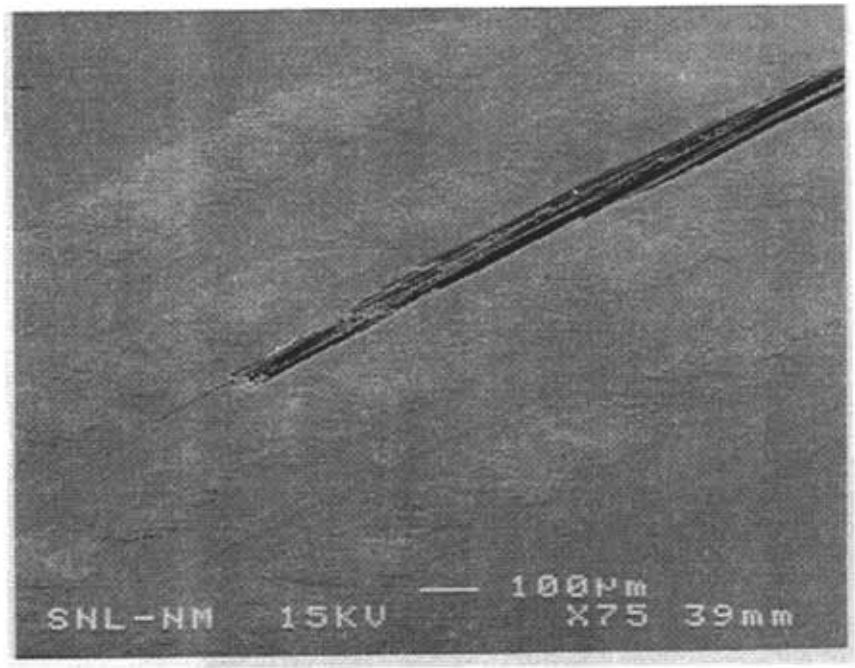

Figure 17: Specimen 4, View 2 (120 s, 10 psi)

#4 10"

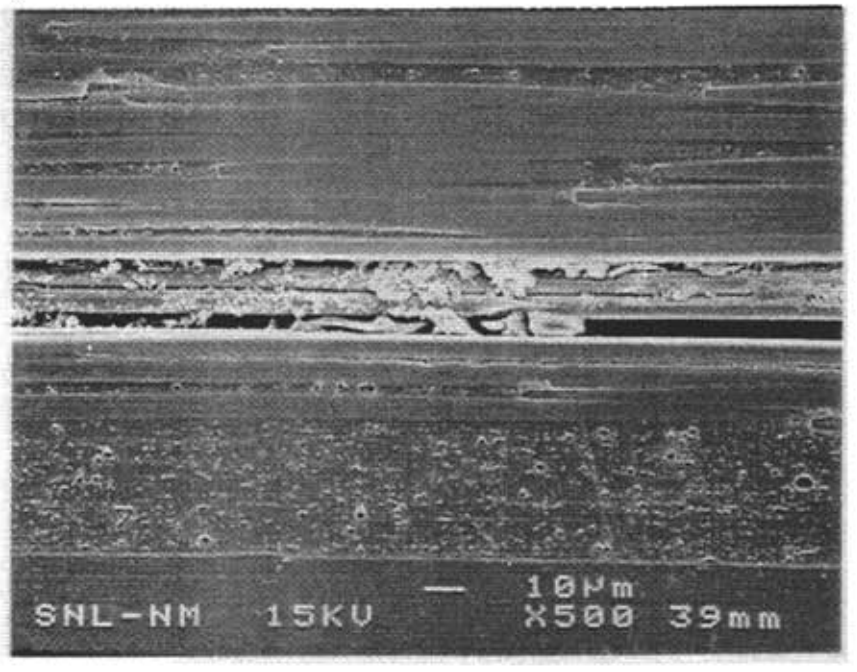

Figure 18: Specimen 4, View 3 (120 s, 10 psi)

Specimen 5 was cured at 120 seconds dwell time and 6 psi. Many voids are present throughout the specimen, not just at the center. The dwell time and the pressure are obviously insufficient to make a quality part.

We conclude that time at temperature is the crucial parameter; further studies will need to identify non-uniformities in the input material and see of they are filled at a longer dwell time.

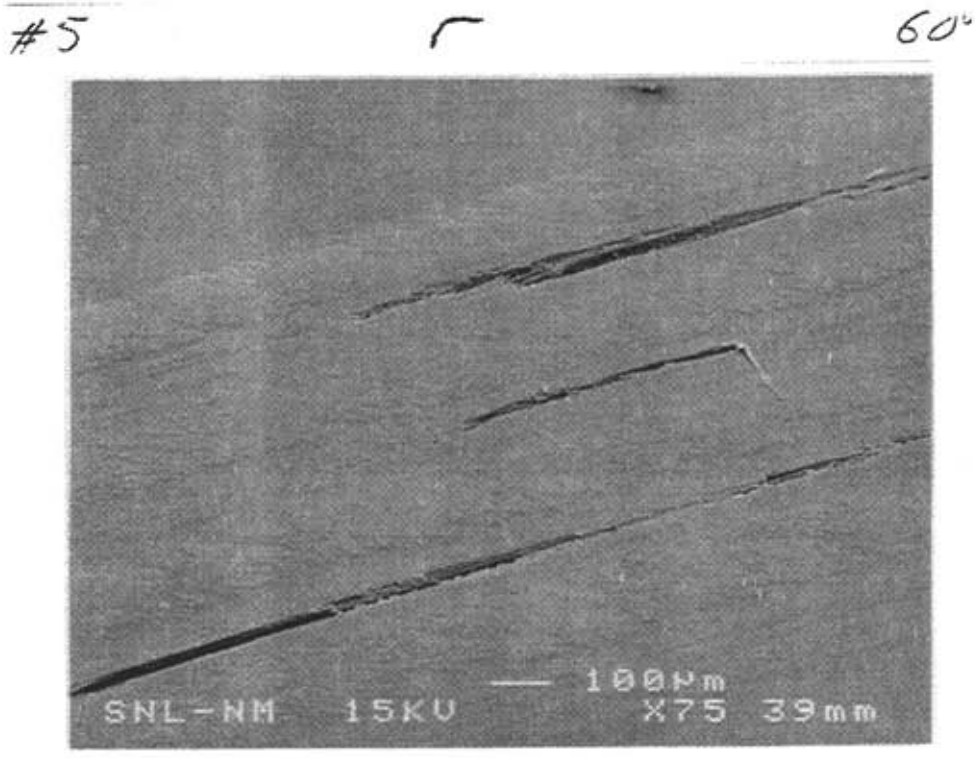

Figure 19: Specimen 5, View 1 (120 s, 6 psi)

#5 10°

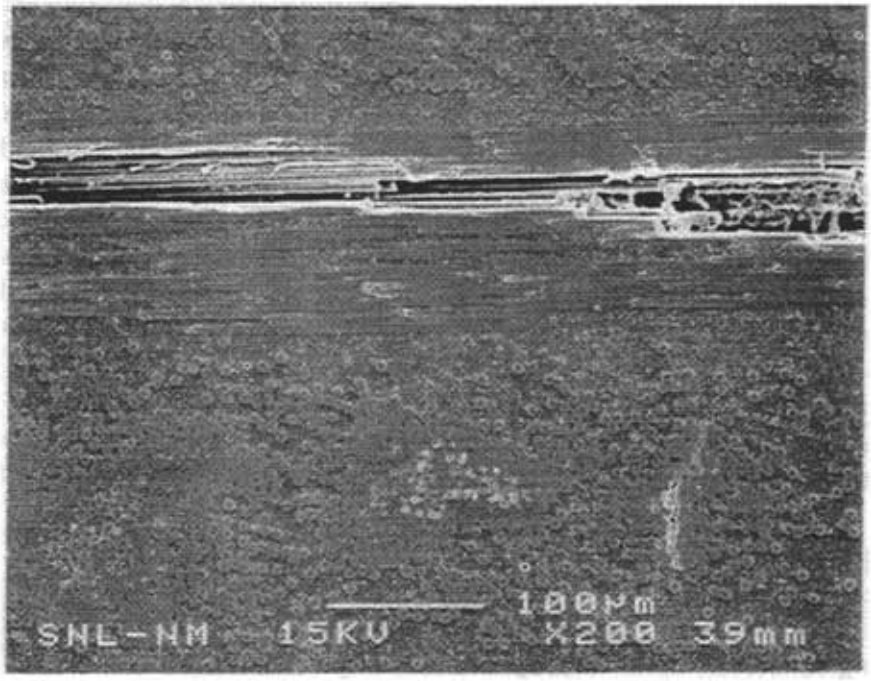

Figure 20: Specimen 5, View 2 (120 s, 6 psi)

7 Outstanding Technical Issues

Heat flow poorly understood The sectioning analysis suggests that minutes are required for the center of the heated patch to reach the melting temperature of the thermoplastic. The anisotropic thermal conductivity of the carbon fibers may be contributing to this, because they conduct the heat in the direction of the fibers. The thermal conductivity of different types of carbon fiber varies widely - from 25 to 1000 W/mK, where W is watts, m is meters, and K is degrees Kelvin ([6]), whereas the thermal conductivity of nylon is approximately 0.25 W/mK ([1], p. 6-192). Therefore, heat flow across the fiber planes is likely to be much slower than that in the planes, because the thermal conductivity of the fibers is at least two orders of magnitude greater than that of nylon. We have observed this effect, in that the material outside the heated patch also melts and flows. Since it is outside the pressurized patch as well, the flow is unconstrained, and can lead to low part quality. One solution to this is to make the pressurized patch larger than the heated patch — currently they are the same size. Certainly we need to better understand the heat flow.

Placing forming apparatus at end of robot arm To make a large structure, it is imperative to place the forming apparatus at the end of the robot arm, and hold the evolving structure stationary. For if the robot holds the part, it can only hold it at one end, and positioning the other end accurately will not be possible over any distance. We are currently working on designing such an end-of-arm apparatus using follow-on funding we have obtained.

Automatic programming of system We spent most of the LDRD effort on understanding the forming process, and therefore did little on programming the system automatically from a CAD model of the desired part. Such programming would most likely be based on a parametric representation of the surface, obtainable from solid modelling software.

Two degrees of curvature in forming apparatus Current and envisioned forming surfaces allow only a single direction of curvature. An obvious desire is to have two directions of curvature, which would be allowed by a "pinhead" contour gauge consisting of individually movable pins. Other implementations may be possible. Then warped surfaces could be made directly. However, this seems to require a high-temperature elastomeric material to replace the spring steel. Our experience with Teflon does not auger well for the surface finish that would be obtained using such a material. Another possibility is to use thin strips of spring steel instead of the sheets we currently use. We have not worked on this to any significant extent.

Using thermoset composites We have only used nylon (thermoplastic) composites. Because working with thermoplastics is not as well understood as working with thermosetting materials (such as epoxies), this method may be a contribution to greater use of thermoplastics and their attendant greater hardness. However, it remains to be seen if the method

can be used on thermosets.

8 Conclusion

We have described a novel rapid prototyping method that produces structures made of continuous fiber polymer-matrix composites, but does not use a mold. We have implemented a prototype, and demonstrated its feasibility, using commingled and preconsolidated thermoplastic and graphite composite material. We have produced cylindrical objects under automatic control using this system. Producing non-convex shapes with the system is obviously possible, simply by reconfiguring the forming surface as appropriate.

A Appendix: Project Metrics

Publications and presentations resulting from the project: [4]

Patent and Invention Disclosures resulting from the project: Technical Advance disclosure SD-5879, "Method and Apparatus for Freeform Fabrication of Composite Structures"; Patent application filed 3/17/97.

Software copyrights resulting from the project: None

Employess recruited to work on the project: None

Student involvement in the project: Two students worked on the project during the summer of 1997: one from the University of Turabo, and one from UNM.

Follow-on work: Lockheed Martin Tactical Aircraft Systems has funded us for $100K (WFO NFE Contract #AL89285) to demonstrate that structures having multiple fiber directions can be made with the method. Further work is likely after that.

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