CHAPTER 6

Pultrusion

1. GENERAL

Pultrusion is a manufacturing process that combines many steps in the manufacturing of composites into two steps. Refer to Figure 1.7(a) of Chapter 1. That figure shows four steps in the manufacturing process. Figure 6.1 shows a representation of the pultrusion process. For pultrusion, one goes directly from step *a* to step *d*, and one does not have intermediate products in between.

- Step *a*: Beginning from the left-hand side, the fiber tows drawn from fiber racks are routed through a series of guides. The fibers then traverse through a bath of low viscosity resin for impregnation.
- Step *d*: Upon exiting from the resin bath, fibers are collimated into an aligned bundle before entering into a heated die. While inside the die, the following takes place:

  —The resin flows and wets the fibers.
  —The ensemble of fibers and resin is compacted.
  —The resin cures and the fiber/resin system becomes solid.

  Upon exiting from the die, the composite structural component is pulled by a puller. It is then cut to length and is ready for shipment.

Since the pultrusion process combines many steps into one, the opportunity for checking the quality is reduced. Also the requirements for control of quality are increased to ensure good quality. However, pultrusion offers a fast production rate. The production rate can be in terms of meters per minute. It can also produce composite parts at low cost. This is because fibers in tow form are less expensive than in prepreg or woven form. The rule is that if more processing is involved in transforming the fiber, either by wetting with the resin or in changing the form from unidirectional tows to woven or braids, cost and time are involved. As such, pultrusion has been used to produce many low cost composite structural elements, if strict quality is not a requirement. However there are also limitations. One of the main limitations is that the fibers are mostly unidirectional.

By pultrusion, many lightweight, corrosion resistant and low electrical conductivity components can be made. These include standard shapes such as rods, angles, clips, I beams, panels, plates, and rebars for concrete reinforcement. Other components include side rails for ladders, fishing rods, tool handles, bus components, sign posts, and sucker rods for oil drilling rigs.

Due to the low cost of the process, E glass fibers are mostly used even though applications include fibers such as S glass, carbon, and Kevlar. Resins are usually low cost polyester or vinyl ester even though other resins such as epoxy, phenolic and thermoplastic have also been used.

There are two forms of pultrusion products. The first category consists of solid rod and bar stock produced from axial fiberglass reinforcements and polyester resins. These are used to make fishing rods and electrical insulator rods, which require high axial strength. The second category is structural profiles, which use a combination of axial

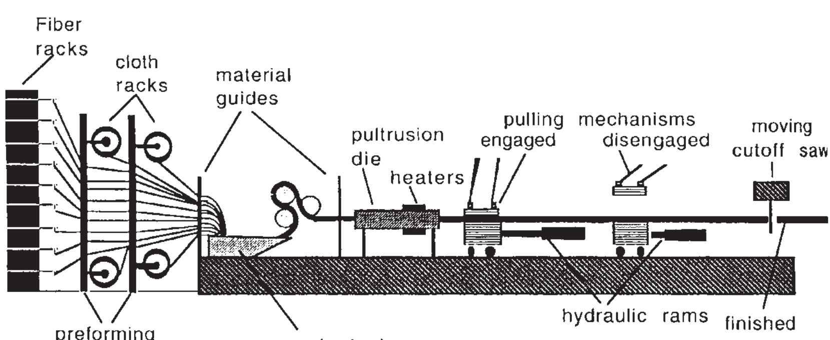

FIGURE 6.1 Schematic of the pultrusion process (reproduced from "Pultrusion of composites," by J. P. Fanucci, S. Nolet, and S. McCarthy, in *Advanced Composites Manufacturing* by T.G. Gutowski, 1997, with permission from John Wiley and Sons).

fibers and multidirectional fiber mats to increase a set of properties that meet the requirements of the application in the transverse and longitudinal directions.

2. MATERIALS

2.1. Fibers

2.1.1. Unidirectional Rovings

Fiberglass is the most commonly used fiber for pultrusion. Unidirectional fibers are the least expensive reinforcements available. Most pultruded profiles are used in structural applications where loading is highly oriented along the length of the profile. Unidirectional loading minimizes friction drag in the die, provides the highest pulling strength possible, and simplifies the design and fabrication of forming guides at the entrance of the die.

The combination of cost, design applicability, and manufacturing ease make unidirectional rovings the most widely used reinforcement in pultrusion processing. Unidirectional filaments in the form of rovings, tows or threads are the building blocks for virtually all other reinforcement forms.

For most practical applications, the use of all-unidirectional rovings is unrealistic. The highly orthotropic behavior of the unidirectional composite results in transverse properties that are much too low. Parts constructed this way might have unacceptable resistance to crushing or splitting parallel to the fiber direction. Some means of providing strength in the transverse direction is often mandatory.

2.1.2. Woven and Nonwoven Broad Goods

Low cost commercial pultrusions made of unidirectional glass rovings often include inexpensive forms of nonwoven broad goods called *continuous strands* and *chopped strand mat.* The random orientation of these materials provides some degree of off-axis strength and stiffness enhancement at very low cost. Woven materials used in the pultrusion process must be placed between more stable forms such as layers of unidirectional rovings. Figures 6.2 and 6.3 show the incorporation of mats along with unidirectional rovings.

When more complicated laminates are required, cloth, random mats, and preplied fabrics can be added to obtain transverse and off-axis rein-

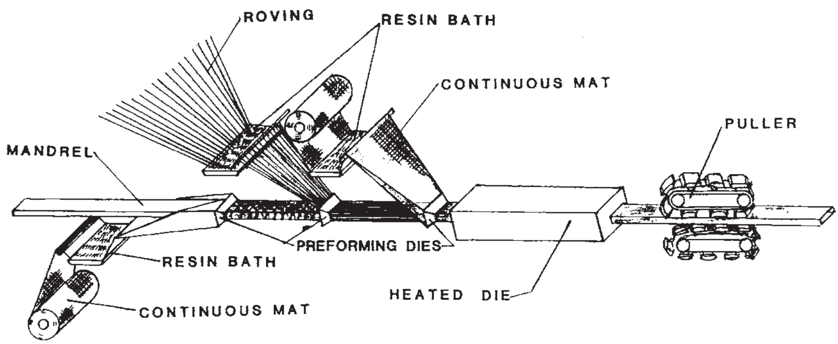

FIGURE 6.2 Introduction of mats into the pultruded products (reproduced from *Handbook of Pultrusion Technology,* by R. W. Meyer, with permission from Springer).

forcing. Fiber tension is not a severe problem for commonly pultruded constructions composed primarily of unidirectional tows. Problems begin to occur in more sophisticated applications when broad goods and other off-axis reinforcements are included in the laminate. If not properly handled, these laminates tend to distort and deform as they are folded during assembly outside the die, and can be further distorted when dragged along the tooling surfaces inside the die.

2.2. Resins

The necessary characteristics for a resin to be used to make pultruded products are that it have low viscosity and that gel time and cure time

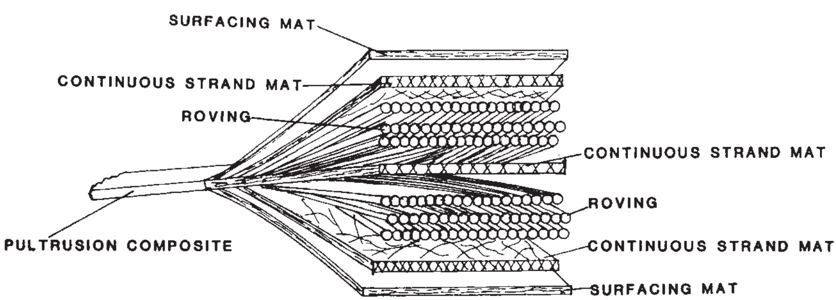

FIGURE 6.3 Exploded view of materials in pultrusion (reproduced from *Handbook of Pultrusion Technology,* by R. W. Meyer, with permission from Springer).

are short to allow for the high rate of production. If, for example, a rate of production of 20 cm/minute is desired, for the length of a die of 100 cm long, the duration of the resin inside the mold is 5 minutes. The resin should flow through the interstices of the tows, wet the fibers, gel and cure during this time. When the resin gels, it also shrinks, which helps to release the composite from the die wall. This, in turn, will reduce the pulling force. The resin normally used to make pultruded products is polyester resin, due to its low cost and low viscosity. Table 6.1 shows the viscosity of polyester resin along with gel time and cure time. When better corrosion resistance is required, vinyl ester resins are used. When a combination of superior mechanical and electrical properties is required, epoxy resin is used. Epoxy resins are expensive materials in a number of aspects. The resins are three to six times more expensive than polyesters and have a number of process-related costs not found with polyesters. Because they are cured by a stepwise reaction rather than an addition reaction, as with polyester resins, their reaction rate is very slow. The gelation of epoxy resins occurs at a later stage of reaction, and it is critical that the exotherm developed be contained within the die. This dictates a slow reaction rate, which results in a high labor. Because the epoxy begins to react slowly as soon as it is mixed, the pot life is short. The resin scrap rate is potentially higher if viscosity buildup affects wet-out to the extent that the bath must be recharged. The die temperature profiles used for epoxy are typically hotter than polyesters, and the drip-off at the entrance must often be discarded rather than recirculated to the bath. Because of the tendency for the epoxy resin to bond strongly to the die wall, epoxy products often display surface defects, such as exposed fibers, chipping, or loss of dimension, all of which increase finished-product scrap rate. These additional costs place epoxy resins in a class in which the end-use requirements must justify the high price [1].

TABLE 6.1 General Properties of Polyester Resins Used for Pultrusion.

Property	Value
Viscosity at 25°C (cP)	500–2000
Specific gravity	1.1
Gel time (minutes)	3–8
Cure time (minutes)	5–18
Peak exotherm (max temperature during the process)	415–470°F (213–243°C)

3. COMBINATION OF OTHER PROCESSES WITH PULTRUSION

As part of the process of automation, other types of processes have been combined with pultrusion to produce parts with enhanced properties. These include in-line filament winding or in-line braiding, together with the pultrusion process.

3.1. In-Line Winding

In situations such as the case of pultruded rods used for the reinforcement of concrete, it is necessary to provide roughness on the surface of the putruded rods to enhance the mechanical interlock between the reinforcement rod and concrete. Filament wound strips can be placed on the outer surface of the pultruded rods for this purpose. At the exit of the pultrusion machine, spools of unidirectional tows loaded onto two counter-rotating disks can be circumferentially wound around the exited pultruded rod.

3.2. In-Line Braiding

In in-line braiding, a vertical braider is positioned in front of the pultrusion die. As the braider pays off the material, the material is drawn forward through the braiding ring and laid down on the mandrel. The resulting fiber angle is a function of the braider speed and pultrusion line speed. Impregnation of the thin walled braids is accomplished via continuous resin transfer molding, called *direct resin injection.* The impregnated braid is drawn into the pultrusion die and the resin is polymerized. The cured tube is manufactured continuously.

4. FACTORS AFFECTING THE PULTRUDABILITY OF A COMPOSITE COMPONENT

Two important characteristics affecting the pultrudability of a composite product are: the pulling force required to move the product steadily through the system and the pulling speed. The pulling force has to be sufficient to overcome the resistance at the different stages of the pultrusion process, and the pulling speed determines the productivity of the process. These are discussed below.

4.1. Pulling Forces in Pultrusion

Controlling the buildup of pulling loads and developing ways to deal with their inevitable presence are major concerns for all pultruders. Preform compaction and the effects of fiber packing in the die contribute the most to pulling force generation during pultrusion. This is particularly true in the processing of epoxies where fiber and filler must be kept high to prevent sloughing or resin adhesion to die surfaces, and to maintain good surface finish.

One way to analyze the parameters that contribute to the pulling force is to examine the contribution of the resistance from each step of the process. As can be seen from Figure 6.1, the resistance should be considered from the four different steps: Force required to collimate the fiber tows from the creel to the entrance to the die, force required to compact the fiber tows into the cavity in the die, force required to overcome the viscosity of the liquid resin, and force required to overcome the friction between the wall of the die and the solid composite product. This can be written as:

$$F_{total} = F_{col} + F_{compaction} + F_{viscous} + F_{friction} \tag{6.1}$$

4.1.1. Force Due to Collimation

The collimation force F_{col} depends on the loading of the fibers relative to the size (diameter) of the die. There is a limit as to the difference between the diameter of the collimated fiber bundles to the diameter of the die. Within limits, the larger the amount of fibers, the larger the F_{col}. One other aspect is the ease with which the fiber bundles are introduced into the die. Figure 6.4 shows the arrangement of a tapered entrance into the die. The taper configuration facilitates the introduction of the fibers into the die and reduces the F_{col}.

4.1.2. Force Due to Compaction

In Equation (6.1), the compaction force F_{comp} is a force along the pull (axial) direction of the process. However, compaction is occurring along the radial direction of the die, which is normally the pull direction. Normally, the greater the number of fibers that are squeezed into the cavity of the die, the larger will be the compaction. If too much fiber is put in, the compaction will be too large and pulling may not be possible. However, if too few fibers are put into the die, insufficient compaction will occur and voids may appear. In addition, there is resin shrinkage, which can

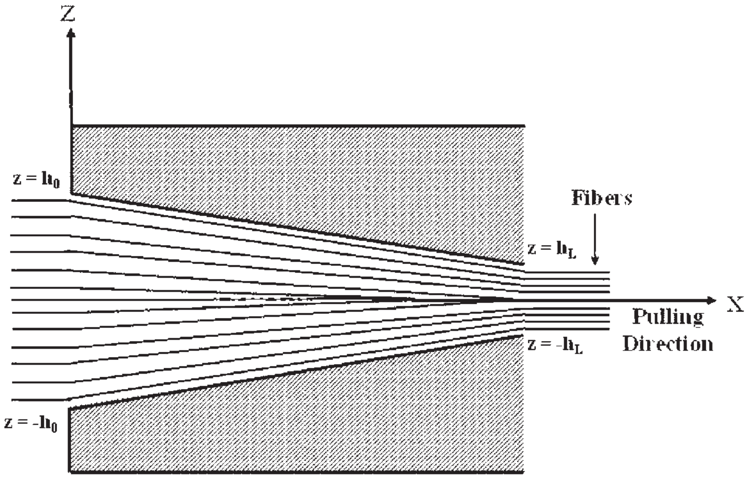

FIGURE 6.4 Tapered entrance facilitates the introduction of fibers into the die.

also affect the compaction pressure. One way to get an estimate of the pressure in the material inside the die is to use Equation (3.13) in Chapter 3, repeated here as:

$$\begin{bmatrix} e_1 \\ e_b \end{bmatrix} = \begin{bmatrix} F_{11} & F_{1b} \\ F_{b1} & F_{bb} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_b \end{bmatrix} \tag{6.2}$$

where,

e_1, σ_1 = the strain and stress along the pull direction
e_b, σ_b = the strain and stress in the radial direction
F_{ij} = the compliance coefficients of the fiber bundles

The strain e_b is governed by the geometry of the die. If R_o is the radius of the die entrance with an initial volume fraction V_o, and R_f is the die radius at the position corresponding to the fiber volume fraction V_f, then the strain e_b is calculated to be:

$$e_b = \frac{R_f - R_o}{R_o} \tag{6.3}$$

The axial strain depends on the degree of waviness of the fibers in the fiber bundle. Refer to Figure 3.19 (Chapter 3), assuming that the length of the stretched fiber can be calculated by:

$$\frac{l^2}{4} = \frac{L^2}{4} + a \tag{6.4}$$

where,

l = the length of the stretched fiber over one cycle
L = the length of the unstretched fiber over one cycle
a = the amplitude of the waviness as shown in Figure 3.19 (Chapter 3)

The strain e_1 can be calculated to be:

$$e_1 = \frac{l - L}{L} = \sqrt{1 + \frac{4}{\beta^2}} - 1 \tag{6.5}$$

where $\beta = L/a$. If $\beta = 200$, one has $e_1 = 0.00005$.

Recall the expressions for F_{ij} from Chapter 3 as:

$$F_{11} = \frac{4}{\pi}\frac{1}{E}\varsigma^2[1 + 2(\varsigma - 1)^1] \tag{6.6a}$$

$$F_{1b} = F_{b1} = -\frac{16}{\pi^3}\frac{\beta^2}{E}\varsigma(\varsigma - 1)^3 \tag{6.6b}$$

and

$$F_{bb} = \frac{\beta^4}{3\pi E}(\varsigma - 1)^4 \tag{6.6c}$$

One can calculate the stresses with information on the strains.

Example 6.1

A pultrusion machine having a radius R_o = 12.7 mm and R_f = 6.35 mm is used to pultrude fiberglass/polyester rod. The desired volume fraction is 0.60. Determine the contribution to pull force due to compaction. Assume $\beta = 200$ and $E = 70$ GPa, $V_o = 0.4$ and $V_a = 0.785$.

From Equation (6.3), $e_b = \frac{6.35 - 12.7}{12.7} = -0.50$

$$\varsigma = \sqrt{\frac{V_a}{V_f}} = \sqrt{\frac{0.785}{0.60}} = 1.144$$

The compliance coefficients can be calculated using Equations (6.6) as

$$F_{11} = \frac{4}{\pi}\frac{1}{E}\varsigma^2[1+2(\varsigma-1)^2] = \frac{4}{\pi}\frac{1}{70\text{ GPa}}(1.144)^2[1+2(1.144-1)^2] = 0.025\text{ GPa}^{-1}$$

$$F_{1b} = F_{b1} = \frac{16}{\pi^3}\frac{\beta^2}{E}\varsigma^2(\varsigma-1)^3 = -\frac{16}{\pi^3}\frac{200^2}{70\text{ GPa}}(1.144)(1.144-1)^3 = -1.009\text{ GPa}^{-1}$$

$$F_{bb} = \frac{\beta^4}{3\pi E}(\varsigma-1)^4 = \frac{200^4}{3\pi(70\text{ GPa})}(1.144-1)^4 = 1043\text{ GPa}^{-1}$$

Equation (6.2) can be inverted to be written as:

$$\begin{bmatrix}\sigma_1\\ \sigma_b\end{bmatrix} = \frac{1}{F_{11}F_{bb}-F_{1b}^2}\begin{bmatrix}F_{bb} & -F_{1b}\\ -F_{1b} & F_{11}\end{bmatrix}\begin{bmatrix}e_1\\ e_b\end{bmatrix} \tag{6.7}$$

For this particular case:

$$\begin{bmatrix}\sigma_1\\ \sigma_b\end{bmatrix} = \frac{1}{26.08-1.02}\begin{bmatrix}1043 & 1.009\\ 1.009 & 0.025\end{bmatrix}\begin{bmatrix}0.00005\\ 0.5\end{bmatrix}$$

$$= \frac{1}{25.06}\begin{bmatrix}0.552\\ 0.0125\end{bmatrix} = \begin{bmatrix}0.022\\ 0.0005\end{bmatrix}\text{GPa} = \begin{bmatrix}22\\ 0.5\end{bmatrix}\text{MPa}$$

Note that due to the small value of e_1, its contribution to σ_1 is about 10% and it has little contribution to σ_b. It can be seen that the contribution of compaction to the axial load is quite significant. Note also that the above calculations are only approximate due to the application of linear assumption to a situation of large deformation.

The above example shows a simplified estimate for the compression stress σ_b due to existence of the compressive strain e_b. The compressive strain in the example is a function of the reduction in geometry of the die from the entrance to the point of interest. This, in turn, is related to the change in volume fraction of the fibers at the different positions. There are other parameters that also have an effect on the relation between the fiber volume fraction and the compressive stress as discussed below.

4.1.3. Parameters Affecting the Compression Stress

Figure 6.5 shows the relation between fiber volume fraction and compressive stress. It can be seen that even though the shape of the curve between compression stress and volume fraction is similar, Different types of fiber forms show different curves but the shapes of the curves are similar, the actual values of the stresses depend on the type of fibers. Apart from these, there are many parameters that affect the compressibility of the fiber bundle, one of which is the fiber volume fraction, as discussed previously. In addition, other parameters affect compressibility as well, such as the type of fiber material, fiber architecture (mat or weave pattern), combination of different types of fiber architecture (mat and roving alternating in different sequences), rate of loading, loading and unloading, repeated loading, and dry or lubricated fiber beds. The fact that the compressibility depends on so many factors makes it difficult to obtain good models that fit all systems. Experimental determination of each different system is therefore essential.

Shrinkage of resin has an important effect on the pull force. Polyesters and vinyl esters shrink about 8% while epoxies shrink about 5%. As such, it would be easier to pultrude polyester of vinyl ester composites than epoxy composites. The amount of fiber loading has an important effect on the pulling force, as shown in the above example.

4.2. Pull Rate

The pull rate depends on the time required for the resin to impregnate

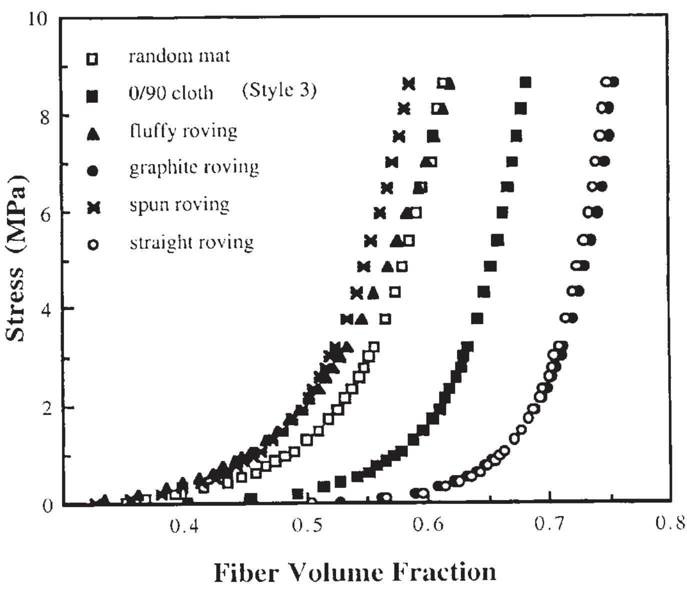

FIGURE 6.5 Compression stress as a function of fiber volume fraction (reproduced from "Pultrusion of composites," by J. P. Fanucci, S. Nolet, and S. McCarthy, in *Advanced Composites Manufacturing* by T. G. Gutowski, 1997, with permission from John Wiley and Sons).

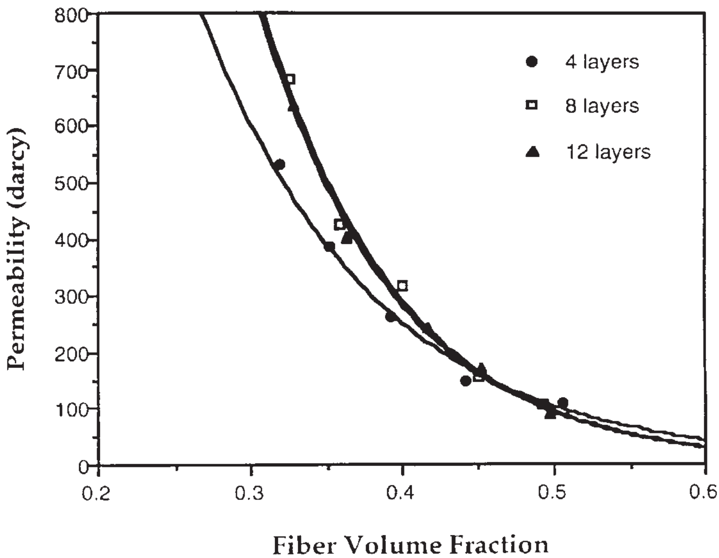

FIGURE 6.6 Effect of number of layers on permeability of 0/90 cloth (reproduced from "Pultrusion of composites," by J. P. Fanucci, S. Nolet, and S. McCarthy, in *Advanced Composites Manufacturing* by T. G. Gutowski, 1997,with permission from John Wiley and Sons).

the fiber tows and also for the resin to cure once complete wetting has taken place. The pultrusion die may consist of two sections along the direction of pulling, the first section is required for wetting to take place and the second section for curing to take place. The pull rate is related to the lengths of these sections. The length of the first section may be estimated using Darcy's law and the permeability of the fiber tows. The length of the second section depends on the reactivity of the resin and the temperature profile along this length.

4.3. Permeability

The permeability of the fiber tows depends upon the type of materials, the number of layers, and the volume fraction of the fibers. Figure 6.6 shows the effect of the number of layers of cloth on permeability.

5. SUMMARY

The state of development of pultrusion as a process for composite manufacturing is still in the experimental stage. This is due to the integration of many steps into the process which makes it complex. The permeability of the resin into the fiber bed varies greatly with the fiber bundles and also varies with the degree of compression of the fiber bed. The rate of reaction of the resin is rapid due to the fast production rate. Pultrusion can produce parts with low cost using low-cost materials such as glass and polyester.

6. REFERENCE

1. Meyer R. W., *Handbook of Pultrusion Technology,* Chapman and Hall, 1985.