PULTRUSION —

HIGH PRODUCTIVITY NOW, GETTING EVEN BETTER

By A. Brent Strong/Brigham Young University

What is pultrusion and why should you care?

Pultrusion is a process for making composite parts on a **continuous basis**. How many other composite processes can you think of that are continuous? Not too many, I bet! Therein lies the importance of pultrusion in the world of composites manufacturing. It is one of the few continuous processes for making composite parts and therefore offers tremendous advantages for high throughput manufacturing. To further add to its value, material usage is very high — with almost all raw materials consumed and almost no trim or other scrap. This is all done with very little labor. Sound interesting? Read further.

Studies have shown that pultrusion is the lowest cost process for making advanced composite parts, that is, the types of products used in aircraft where fiber placement and part performance are a premium (Fanucci 1992, Krolewski 1986). These data assert that pultrusion costs are only 41% as much as filament winding and only 26% as much as prepreg hand layup. The cost comparisons with wet resin processes such as layup and sprayup have not been done, but the high throughput and of pultrusion seem to point to very low costs even compared to sprayup and wet layup. Do you find that to be intriguing? Believable?

But all is not completely perfect. Pultrusion has some significant limitations and these have restricted its use. Some of these limitations are now being overcome, as will be described later in this article, but the historical limitations are important to understand because they have dictated where and for what pultrusion was used. Moreover, even though some of the limitations are now being improved, none are being completely eliminated.

The most important limitation is that parts made by pultrusion have constant cross-sections, much like extruded metal or plastic parts. For instance, parts can be hollow (like pipes or tubes), or solid (like rods), or shaped (like I-beams, channels and angles), but they cannot vary in shape along their length. The parts are generally long and straight with their greatest strength in the long direction, because that is the principle fiber direction. Dimensional accuracy is fairly good, but other manufacturing methods can be better (although pultrusion is about as accurate as sprayup and wet layup). Fiber and resin contents and uniformities can be at least as good as wet layup and sprayup. Processing problems, some unique to pultrusion like resin buildup on the die, also limit the process.

In spite of these limitations, pultrusion is becoming much more versatile and offers some advantages for a wide variety of parts, some of which cannot be economically made with other processes. Parts currently made using pultrusion include the following (Goldsworthy 1991):

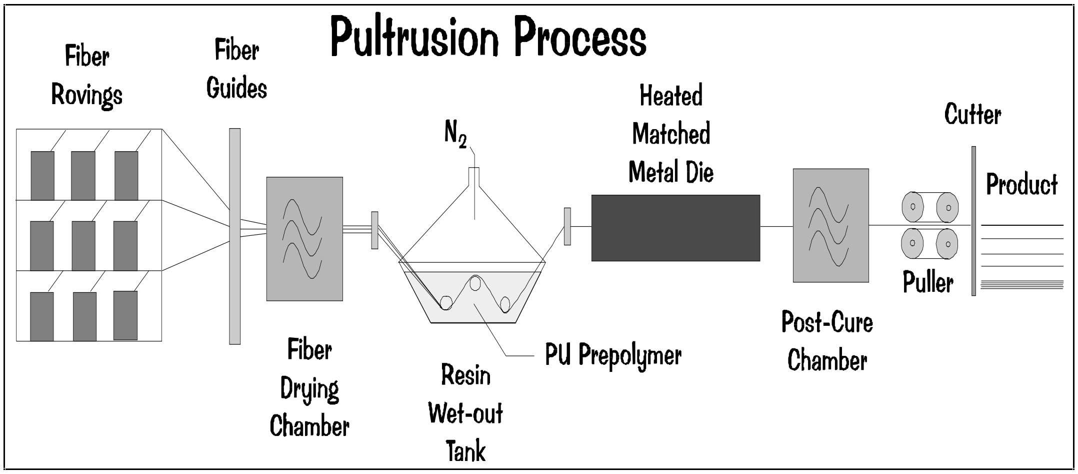
- **Consumer parts** such as: stadium seating, flag poles, fence posts, drapery rods, fishing rods, hockey sticks, bows/arrows, ski poles, boat parts (masts, spars, booms), tool handles, snowmobile track rods.
- **Construction parts** such as: building panels/shelves, highway delineator posts, window parts, door jambs, mine roof support beams, fabricated structural shapes, bridge girders, suspension cables, offshore drilling rig components, architectural columns, and hand stair rails.

- **Electrical/energy parts** such as: cable trays, transformer (stand-off) spacers, insulating channels, conduits, tree trimming poles, wind turbine blades, aerial booms, and ladders.
- **Corrosion resistant parts** such as: water tubes, flue gas scrubber parts, pipes, forms for concrete, flooring/grates, and exhaust ducts.
- **Transportation parts** such as: automobile leaf springs, automotive transport train cars, aircraft components, trailer structural beams, trim parts, ship/submarine components, and monorail structural and decorative components.

Notice that almost all of these parts are high volume applications. If your part is similar to these, you might want to try pultrusion.

The Traditional Process

The pultrusion process, as most commonly used, is depicted in Figure 1. Dry fiber tows are drawn off spools or creels and threaded through a grating system that collects and aligns the fiber tows into a fiber bundle. Most of the familiar reinforcement fibers (fiberglass, carbon fibers and aramid fibers) can be used. When pultrusion was originally conceived, only unidirectional fibers (all fibers oriented in the machine direction) were used, thus limiting the types of products that could be made. Today, parts which require fibers in other directions are commonly made by introducing fiber mats or cloth. These are simply joined with the unidirectional fiber tows by using forming rollers and converging sleeves which direct the broadgoods to appropriately merge the broadgoods and tows. Tows in the machine direction are still needed to provide enough strength to pull the entire fiber bundle through the machine.



The fiber bundle is then directed into a resin bath where the fibers are soaked with resin until they are completely wetted. (In some systems, the mat and/or cloth fabrics are joined to the unidirectional fibers after the bath, although this is a minor detail and is not universally practiced.) The wet-out is enhanced in some systems by using rollers and spreading bars within the resin bath. The viscosity of the resin should be thin enough that wetout is readily accomplished. Furthermore, the pot life of the resin should be sufficiently long that curing in the resin bath is not a problem. This latter requirement usually dictates that a heat-activated cure system be used. Pigments and fillers can be added to the resin in the resin bath, but the restriction of low viscosity for good wet-out must be observed. The wetted fibers are squeezed to remove excess resin (which returns to the resin bath) and the fibers are directed into a heated die.

The die is the heart of the pultrusion system and is the limiting step in production rate since the part is both shaped and, usually, cured in the die. The processes of shaping and curing along with the correspondent line speed are dependent upon the shape of the part, the type of resin, the internal friction in the die, the heat expansion of the resin, the contraction of the resin, and mechanical warpage which may occur in the part because of non-symmetries in the fiber orientations.

The opening of the die is usually somewhat larger than the final shape, permitting easy collection of the fibers bundle, and then the die interior dimensions gradually reduce in size until the final shape is achieved. During this shaping process, the part is cured.

Cure is accomplished either by thermally heating the die (usually with common electrical heaters) or by subjecting the material to rf frequencies. Both of these systems have their advantages. The thermal heating is simple and can be used with metal dies, thus limiting die wear. However, the poor heat transfer of the resin means that as the thickness of parts increases, the speed of the pultrusion line must slow. Studies have shown that thicknesses of about .5 inches can be thermally cured at 2 feet per minute but that parts thicker than 3 inches cannot be cured at all using just thermal energies, regardless of the line speed (Goldsworthy 1991).

If rf curing is used, the thickness of the parts which can be cured and the line speeds possible are both improved — about 3 times faster with parts that are .5 inches thick (Goldsworthy 1982). However, rf curing does not work well for metallic dies nor for conductive parts. Hence with rf curing, non-metallic dies are generally used and these are prone to rapid erosion and poor dimensional control. Parts with conductive components (such as carbon fibers) cannot be effectively cured using rf radiation. These materials are thermally cured. Recent machines which combine both thermally heated metal dies and rf heating after exiting the die have proven to give much better performance than either of the methods alone.

Parts must be quite hard (essentially cured) when they exit the die so that they will not be deformed by the pulling mechanism, although some curing after exiting the die is possible if done before the pullers. Post-die curing can be done with a tunnel heater, although this adds considerable length to the line and is notoriously inefficient in heat use. Another method of post-die curing is to use heated, moving C-shaped dies (also called split dies) that have cavities in the shape of the finished part and close on the part as it exists the die. These dies are mounted on a moving belt or chain and stay in contact with the part long enough to insure that sufficient cure is achieved to withstand the forces of the puller. Off-line curing could then be used, as required.

The puller system is usually of two types. One type uses part-shaped grippers which, in sequence, engage the part and pull it along for a short distance (usually about 3 feet) and then pass the part on to another set of grippers, thus giving the part a uniform pulling action. The second type of pulling system uses double continuous belts or caterpillar pullers. These pullers engage the part and move it along at the speed of the belts.

Part cut-off and packaging is done after the puller. Cut-off is usually done with a saw that moves with the speed of the line, thereby ensuring that the cut edge is straight.

Resins

Most of the traditional resins used for composite materials can be used in pultrusion, although many are modified to meet the particular requirements of pultrusion. Even when modified to achieve optimum results, some resins have significant deficiencies.

By far the most commonly used resins are unsaturated polyesters and vinyl esters, both usually employing styrene as the solvent/crosslinker. Because of the need to avoid gelation in the resin bath, standard heat-activated cure systems (peroxides) are used. The loss of styrene in the resin bath can be a problem in polyester and vinyl ester systems since the change in styrene content can affect both viscosity and extent of cure in the final part. Too much styrene, on the other hand, can result in residual styrene in the part; a problem that can lead to poor physical properties and objectionable odors.

Epoxies can also be used in pultrusion, but they tend to stick to the die much more than polyesters and vinyl esters. This increased sticking occurs because epoxies are both better adhesives than polyesters/vinyl esters and, further, epoxies shrink less, therefore tending to remain in intimate contact with the die whereas the polyesters and vinyl esters shrink away. Nevertheless, epoxies are used in pultrusion when high corrosion resistance or improved thermal or mechanical properties are needed.

Phenolic resins can also be used, especially when low flammability is needed, but they cure more slowly than the other resins and also produce a condensation product (water) during the crosslinking process. The net result is that phenolics run more slowly and have a poorer appearance than polyesters or vinyl esters. Sticking in the die is also a major problem with phenolics.

Thermoplastics are not commonly used in pultrusion. However, they can be useful when high impact strength is needed or when the part is to be thermally formed after being pultruded. The major problem with thermoplastic resins in pultrusion is achieving good wet-out of the fibers. Thermoplastic resins are usually much thicker than thermoset resins and will not conveniently wet-out the fibers in a reasonable time. Some manufacturers have added solvents or plasticizers to the thermoplastic resins to reduce the viscosity. These solvents and plasticizers then need to be removed after the part is formed. The viscosity of the thermoplastic resins can also be reduced by using resins of lower molecular weight, although this approach has had some limited use because parts usually have lower physical and mechanical properties.

Improving the process

Recent innovations have resulted in major improvements in the pultrusion process. Manufacturers and operators of pultrusion equipment seem to have improved each important problem areas of pultrusion.

Innovative wet-out

The replacement of the traditional resin bath with a resin injection system is one of the most significant of the process improvements. Because the injection system is enclosed, the evaporative loss of solvent (usually styrene) has been essentially eliminated (reduced by 99%). This has resulted in a more stable and consistent resin supply and has reduced emissions from the process. Resin injection has also resulted in improved fiber wet-out, thus improving resulting part properties.

Resin injection also allows the use of fiber preforms which can improve the placement of fibers and, therefore, the resulting mechanical properties. These preforms are made by carefully shaping the dry fibers as they move from the creel and spools to the resin injection point. Mechanical guides form and then hold the fibers, mats, fabrics, or multi-layer broadgoods as they move along the line, are injected with resin, and enter the die. Preforms of this type are especially useful when hollow parts or parts requiring three-dimensional reinforcement are made.

Thermoplastic resins have been injected into a bundle of fibers by mounting an extruder so that the fibers pass through the extrusion die. In this way, the fibers are coated with the thermoplastic resin while it is molten. This process usually requires an extended forming die after the exit of the extrusion die so that the thermoplastic resin will have sufficient time to wet-out the fibers. The forming die also gives the final shape to the part as cooling occurs within the forming die.

Two related innovations are the processes called Continuous Liquid Composite Molding and Continuous RTM. In these processes, a continuous sheet of composite is made by injecting resin into a wide sheet of broadgoods or into a preformed, continuous sheet, often several layers thick. The resinous sheet is then passed between rollers to achieve good fiber wet-out and is then pressed to give uniformity in thickness. The resinous preform is introduced into a die and the constriction of the inside dimensions of the die compresses the fibers of the preform. The continuous sheet or continuous preforms can be cut to lengths that are convenient for handling. The sheets, if they are made from thermoplastic resins, can then be layered to the desired thickness and thermoformed to the desired shape.

Innovations in curing

The use of microwaves (Goldsworthy 1991, Lin 1993) has proven to be useful for the improved curing of some parts. Microwaves have superior penetration when compared to rf waves for some resins and can, therefore, give faster cures for thicker parts. The relationships of energy absorption, penetration and radiation frequency are somewhat complicated for each separate resin, so the optimum curing system cannot, in general, be identified without experimental confirmation.

Curing through induction heating has also been shown to be effective for some composite parts, especially those with conductive fibers (such as carbon fibers). When a conductive material is present, either as the fibers or as an additive, the part can be cured by inducing passing the part through an electrical field, thereby creating magnetic-coupled heating. This heating can be very intense, thus giving rapid and complete cures.

Pulforming

This innovation allows parts of non-constant cross-section to be made. In pulforming, a partially-cured part is placed into split dies (molds) as it exits the main pultrusion die. The split dies impart the desired shape to the parts.

Automotive leaf springs are produced by pulforming. Each of the molds is the shape of the completed leaf spring — narrow and thick on the ends, wide and thin in the middle, and curved overall. The molds are mounted on a moving belt that goes around a curved frame which exactly matches the curve of the dies. Hence, the parts are simultaneously gripped and pulled by the dies and the belt, pressed into the molds, forced around a curve, and cured. A cut-off device, mounted at the exit point of the curved forming frame, separates the leaf springs at appropriate sites between the molded portions.

Summary

Are you ready to try pultrusion? It has some advantages if you want to make parts that are either constant cross-section or nearly so. But, the high production rate of the pultrusion process suggests that it be used chiefly for high volume production. If these two criteria are met, you may want to consider pultrusion, especially if some of the recent process innovations can be utilized.

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