COMPOSITE APPLICATIONS IN SPORTS EQUIPMENT: TABLE ROLLING OF COMPOSITE TUBES

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SUMMARY: Table rolling is a common and cost effective composite manufacturing process for tubular structures such as golf shafts, fishing rods, and bicycle tubes. Sheets of pre-impregnated composite material are wrapped around a mandrel which defines the inner shape of the part. A compacting tape is spirally wrapped around the uncured material to debulk the structure and to provide consolidation during the curing process. Once cured, the mandrel is extracted, the consolidation tape is removed, and the outer surface is sanded and subsequently painted. Table rolling allows a multitude of design options by varying the material type, pattern shapes, and mandrel design. This paper presents a short summary of the table rolling process, the equipment, and potential problems and solutions common to the industry. In addition, a partial list of material, equipment, and tooling vendors associated with table rolling is included.

KEYWORDS: tube rolling, golf shafts, bike tubes, table rolling, recreation tubes, mandrel extractor

INTRODUCTION

In the field of composites fabrication, table rolling is a widely used and cost effective technique for utilizing pre-impregnated fibrous tapes which are cut into flag or pennant form for tubular structures. The individual flags become part of the total wall thickness by rolling the flags around a mandrel. The hard mandrel provides the support during cure and defines the inside dimensions of the tube.

Table rolling is utilized to fabricate a variety of products including straight tubes usually under 7.62 cm (3 inches) in diameter and up to 3.66 m (12 feet) long, and small diameter tapered tubes such as fishing rods, golf shafts, and ski poles. Flags may consist of a wide variety of fibers oriented either longitudinally (along the axis of the tube) or off set at a bias angle. In turn, tube rolling patterns are generally referred to as “longitudinal” or “bias” flags. The resin content (RC) and the fiber areal weight (FAW) of the pre-preg define the ply thickness. Since external molds are seldom used for table rolled tubes, a variety of polymer compaction tapes are used to apply an external pressure. These tapes provide the external pressure necessary to debulk and prevent flag unraveling before cure and to provide some heat driven compaction during cure.
Fibers and Resin

Carbon fiber 234 MPa (34 Msi) to 620 Mpa (90 Msi), glass “E” or “S” type, aramids polyethylene, and boron are some of the common fibers in table rolled tube manufacture.

The most common resin used to coat the fibers is the epoxy blend family, which is formulated for specific product purposes. The resin and fiber are combined and advanced slightly to a selected tac (stickiness) level. This fiber and resin combination is called “pre-preg.” Pre-preg surface tac has an important adhesive quality in table rolling which permits composite flags to adhere to one another or the mandrel without slipping during the table rolling operation.

Pre-preg is offered by specification of fiber areal weight (FAW), resin type, resin content (RC), and roll width. Fiber areal weights from 130-160 g/m² and resin contents from 30-36 percent are common in table rolling. Higher modulus fibers favor a lighter FAW to ease rolling. The epoxy in pre-preg is catalyzed, so care must be exercised in following the pre-preg vendor’s storage and handling recommendations. And because air and moisture are detrimental to the surface tac, it is important to cut and consume the flags as soon as possible after opening and unrolling the pre-preg. Dry and low tac pre-preg can influence and aggravate flag wrinkles and ply slippage, leading to voids and dimensional problems. Address tac with the pre-preg supplier to find a suitable resin formulation for the table roller’s manufacturing environment.

Design

The design of a tube rolled part depends on the fiber orientation of the plies, the type or mixture of materials, and the wall thickness. Golf shafts generally consist of +/-45° layers for torsional stiffness and 0° layers for flexural stiffness. Fishing rods mainly incorporate unidirectional fiber with a fine woven glass scrim backing for hoop strength. Bicycle tubes are generally quasi-isotropic, and if the tubes are internally bonded to an aluminum lug, an inside layer of glass is utilized to inhibit galvanic corrosion. The number of layer wraps at a specific orientation is depended on the design and the ease of manufacturability. Also, it is extremely important to design the flag width to completely cover the mandrel circumference and to avoid gaps or overlays of the layers. Indexing or evening offsetting subsequent layers also helps in maintaining a uniform wall thickness and part symmetry. Occasional, however, trade-offs are sometimes accepted to simplify the manufacturing process at the sacrifice of achieving a perfectly symmetrical lay-up.

EQUIPMENT

Shear/Sheeter

Pre-preg materials are generally supplied as a roll of material. The shear or sheeter is a machine which cuts the roll to length. A number of commercially available power sheeters have hardened steel blades and include automatic feed mechanisms for the material rolls. Safety guards with interlocks are needed to prevent finger and hand injury.
Fig. 1: Sheeter Press, Courtesy of Century Design, Inc.

**Roller Press**

The roller press is a machine used to press several stacked layers of pre-preg tape into individual flag or pennant patterns. The cutting tooling used in this machine is the steel rule die.

The steel rule die, the pre-preg, and an impact sheet (usually a soft plastic like polyethylene) are passed through the rotating pressure wheels of the roller press. After compaction, the impact sheet is removed to expose a stack of ready-to-assemble flags which are now nested between the blades of the die. The roller press and dies act similarly to a kitchen cookie cutter. A sharp knife and straight edge is a simple solution for prototype or small scale production flag cutting.

**Rolling Table**

In the 1960s machines with a rotating and movable lower platen were specifically developed for the tubular composite industry. After activating the machine, a pivoted upper platen is lowered down upon the mandrel, and a linear motion activator in the lower platen rolls the mandrel into the pre-preg flag. These machines permit pressure ranges to be established, gaining maximum compaction and increasing the speed of rolling. The pivoted upper platen permits the combinations of parallel tube or tapered (cone-like) tube rolling. If the mandrel is parallel, then the pivot function of the upper platen will be unnecessary.

Current rolling tables include temperature controlled platens and platens with piano key-like fingers for achieving uniform pressure on tapered parts. Both flat bed and segmented bed versions are covered with canvas. This pad provides sufficient resiliency and friction to permit flags to roll without slipping, yet conform to the mandrel surfaces. A slight dusting of
talcum powder can be used to prevent pre-preg from sticking. Table rolling provides tighter and a more uniform compaction of plies than hand rolling.

![Roller Press](image1.png)

**Fig. 2: Roller Press, Courtesy of Century Design, Inc.**

![Table Rolling Press](image2.png)

**Fig. 3: Table Rolling Press, Courtesy of Century Design, Inc.**

**Vertical Tape Wrapper**

A variety of plastic and/or cellophane tapes, 1.27 to 2.54 cm (0.5 to 1.0 inches) in width are used to compact the table rolled plies of pre-preg. Machines used to apply these tapes must permit tape tensioning to debulk the product as the tape is applied. Some applications call for multiple passes through the tape wrapper to increase the tape pressure for better compaction. As the tube diameter or the wall thickness increases, the compaction affect of the tape diminishes so additional wraps of tape are applied. Frequently, two types of tape may be used:
a release tape (polyethylene) and a secondary compaction tape (polyester or cellophane). Apply the tape as soon as possible after table rolling to prevent the flags from loosening.

**Horizontal Tape Wrapper**

This machine represents an alternate to the vertical tape wrapper. It is used frequently for longer, heavier parts and also for very flexible mandrels such as fishing rods. The mandrel is affixed to a chuck or mechanical coupling which rotates the parts while tape is applied. The rollers provide support for the part while motion is in place. The single or even dual tape feed spools move with the tape carriage and return to restart position.

After cure, the wrapping tapes are removed by slitting the tape longitudinally and peeling the tape away from the cured part. Wrapping tapes are then discarded.

![Horizontal Tape Wrapper](image)

*Fig. 4: Horizontal Tape Wrapper, Courtesy of Century Design, Inc.*

**Mandrel Extractor**

Tubular parts which have been cured over a hard mandrel are all subject to mandrel removal. The mandrel extractor generally connects to a bolt on the larger shank end of the mandrel. The end of the composite tube rests against a stationary block shaped to permit passage of the mandrel but blocking the tubular part. Mandrel extractors are generally hydraulic or pneumatic. Hydraulic extractors offer a controlled extraction speed, while pneumatic extractors are faster and useful in high volume environments. Mandrel withdrawal is generally done prior to tape removal.

The type of mold release used, correct size of the stationary block, and the wall thickness of the cured part must be carefully evaluated to prevent end crushing or splitting of the tube.
Very light weight golf shafts with a wall thickness as thin as 0.5 mm (0.020 inches) are possible with the table rolling and shrink wrap process.

![Image of a pneumatic mandrel extractor](image)

**Fig. 5: Pneumatic Mandrel Extractor, Courtesy of Century Design, Inc.**

**Curing Ovens**

Ovens used for curing the composite tubes can be either electrically or gas heated and of batch or conveyorized design. Curing temperatures ranging from 121°C to 191°C (250°F to 375°F) are most common for roll forming pre-pregs. Consult the pre-preg supplier for recommendations on appropriate cure profiles. Fine tuning of the cure profile is often needed to optimize particular roll forming operations and specific products. Ovens with thermocouples are useful in determining hot and cold spots, which may indicate oven regulation for uniform temperature control. This assures a uniform gel and uniform tape compaction within the part.

**Centerless Sander or Grinder**

The wrapping tapes leave a series of spiral indentations approximately 0.05 mm (0.002 inches) deep in the composite tube surface. If a smooth surface is desired for cosmetic reasons or for geometry requirements the part can be surface sanded or ground. A centerless sander basically removes a user defined controlled amount of surface material. A centerless grinder provides a more accurate finish dimension. Centerless grinders are common for the high precision required for the tip ends of golf shafts in which a tolerance of +/- 0.05 mm (+/-0.002 inches) is not uncommon. In carbon fiber golf shaft manufacture, these surface finishing techniques are also used to tailor the product stiffness by incrementally removing material along the shaft length. This changes the shaft stiffness characteristics.
TOOLING

Mandrels

The mandrels used for table rolling are usually hardened steel, sometimes aluminum or even composite. Golf and fishing rod mandrels are usually solid while larger tube mandrels are hollow. The mandrels are designed to support the pre-preg during rolling and curing and provide the inside dimensions for the part. Recalling that mandrels must be extracted in “mandrel extracting,” some negative taper is beneficial. Hard chromed and plated mandrels generally provide a longer life and easier release since scratched or dented surfaces will hamper mandrel removal.

Steel Rule Dies

These dies incorporate multiple blades embedded in a rigid backing (usually marine grade plywood) which cut the material in the roller press. The pre-preg tape (up to 20 layers) is cut between the cutting die blades and a polyethylene sheet sandwiched between the rotating press wheels. Dies with one piece blades provide the best and most continuous cuts. Dies which include weldments (as in a triangular shape flag) generally dull faster since the weldments soften the cutting edges. Ramps can be used between the cutting blades in die designs to keep the roller pressure off the blade ends. The die builder can recommend blade height and cutting edge type best suited for the task.

MATERIALS

Mold Releases

Generally, mold releases for table rolling mandrels consist of two components: A primary mold release which provides a polymer bond to the mandrel surface to prevent adhesion; and a secondary mold release which acts as a slip agent.

The secondary mold release is most beneficial in straight or slightly tapered mandrels and is reapplied between subsequent mandrel turns. A primary release can lose its effectiveness after several hundred turns and must be stripped off and recoated. A variety of quality mold releases are on the market. The fabricator should work with the release supplier to develop a coating program for the specific application. Silicone based releases should be avoided if the tube is subjected to subsequent bonding or painting.

Fibers

The pre-preg tapes can be made from longitudinal tows or woven tows of the following fibers: aramid, glass, carbon, and boron. Most material vendors have developed robust resins and standard fiber packages specifically designed for the cost conscious recreation industry. Many of the in-depth certification programs, panel testing, and other qualification programs common with the aerospace industry are not necessary.

All of these fibrous composite tapes can be cut into flags and pennants needed for the table rolling process. However, because of the brittle nature of boron pre-preg, boron is often hand cut and used generally as a longitudinal tip reinforcement in golf shafts.
TYPICAL PROBLEMS

Voids

Voids are caused by entrapped air which is not evacuated before resin gelation. The presence of voids reduces the strength bearing capabilities of the part, creates stress risers, and can contribute to surface finishing and cosmetic problems.

Voids are first minimized by working with the pre-preg supplier to assure a high quality material with uniform resin content and good “wet-out” of the fibers. Also, the material suppliers (pre-preg and wrapping tapes) must play a key role in developing a cure profile for the specific process and products.

Voids are increased by flag wrinkles which are indicative of rolling problems. The capability to perform void content checks (ASTM D3171) and photomicrographs of the laminate is extremely useful to develop and improve tube processing. Laminate photos are also very useful in operator training. Few laminates are completely void free but void contents lower than one percent are possible with the table rolling and tape wrap compaction process.

Dry and Difficult to Roll Material

Pre-preg dryness (lack of tac) can be due to low resin content, resin formulation, ambient conditions of the manufacturing environment, the age or out time of the material. Insufficient tac can cause flag movement during assembly, wrinkles, voids, and parts with a poor surface finish. Resin content and formulation can be adjusted to suit the manufacturing environment. Temperature and humidity control are very helpful in maintaining consistent material tac in the manufacturing shop. Avoid leaving cut patterns exposed since moisture in the air greatly affects the material surface tac and sometimes renders it useless. Consuming the material within two days is a good rule to follow.

Warm lay up and rolling tables can help increase material rolling ability and are generally adjusted for slight material and environmental changes. Off angle plies are difficult to roll adjacent to the mandrel and the difficulty is magnified by the higher modulus fibers. Tac tape is a narrow strip of reinforced adhesive designed to aid the adhesion of bias plies to the mandrel. Also, solvent based “tac resins” can be applied to the mandrel to ease application of the first ply. Once the first ply is tightly rolled, however, the material tac is sufficient for subsequent flags.

Part Slippage During Cure

The viscosity of the resin drops as the heat of cure begins. Occasionally, tapered mandrels and the constriction of the wrapping tape during the cure can force a part to slip down the mandrel. Golf shaft design is highly dependent on mandrel reference position for proper stiffness and geometry requirements. Slippage can first be minimized by designing a short semi-parallel section in the mandrel (as in the butt section of the golf shaft). Slippage is also reduced by overwrapping the tapes onto the mandrel at both ends to secure the part. In addition, the cure profile or the mold release can be adjusted to limit slippage.
Exposed Surface Voids

Exposed surface voids after sanding or grinding are indicative of poor rolling practices, insufficient lamination pressure, and questionable material. Exposed surface voids are sometimes referred to as “fiber pulls or picks”, which have a wood grain appearance on parts with longitudinal surface plies.

Longitudinal Ply Waviness

Tapered parts with longitudinally oriented fibers are prone to zones with a wavy or “fiber wash” appearance. The problem is amplified with multiple taper mandrels and very low viscosity pre-pregs. Cure profile modifications or alternate resins can reduce the tendency of “fiber wash”.

PARTIAL LIST OF TABLE ROLLING SUPPLIERS

Equipment

Century Design Incorporated
3635 Afton Road
San Diego, CA  92123
(619)-292-1212

Materials

Pre-preg
Newport Adhesives and Composites
1822 Reynolds Avenue
Irvine, CA  92714
(714)-253-5680
Fiberite
4300 Jackson Street
Greenville, TX  75403
(903)-457-8554
Toray
5729 Lakeview Drive, NE
Kirkland, WA  98083-2548
(206)-827-9029
Cytec Engineered Materials, Inc.
1440 North Kraemer Boulevard
Anaheim, CA  92806
(714)-666-4349

Mold Release
Frekote Products
P.O. Box 540083
Orlando, FL  32854-0083
(407)-425-2066

Wrapping Tapes
Flexicon Pacific Inc.
Dunstone Company, Inc.
856 North Elm, Suite J
2104 Crown View Drive
Orange, CA  92667
Charlotte, NC  28227
(714)-633-9820
(704)-841-1380

Tooling

Mandrels
Lynco Grinding Corporation
5950 Clara Street
Bell Gardens, CA  90201
(213)-773-2858
Steel Rule Dies
Ontario Die Company of America
2735 20th Street, Box 610397
Port Huron, MI  48061-0397
(810)-987-5060