Abstract

Filament winding is the oldest and most frequently considered process for machine dominated composite structures manufacturing. It is the process in which continuous strands or filaments of fiber are wound on a supporting form or mandrel. Its best use is for making tube- and pipe-shaped objects, such as high-pressure storage tanks, rocket motor cases, and launch tubes, and for commercial applications, such as golf club shafts and fishing rods. A variety of fibers and resin can be used, depending on the cost and the level of performance needed. In general, fiberglass is the least expensive, but it has the lowest performance level; carbon fibers are the most expensive but have the highest performance level. The principal toolings (so-called winding mandrels) in common use in industry include water-soluble sand mandrels, plaster mandrels for low-volume products, collapsible mandrels, and unremovable liners such as load-sharing metal liners or no-load-sharing plastic liners for pressure vessels. This paper presents a general overview of filament winding technology, including basic design considerations, tooling concepts, metal liner fabrication, winding pattern development, and inspection methods. Two filament-wound composite structures are reviewed: metal-lined composite pressure vessels and composite rocket motor cases.

Keywords: Filament winding; Composite structures

1. Introduction

For years the primary goal of manufacturing and process engineering has been to incorporate automated advanced composite manufacturing techniques into different structures. The industry is looking for weight and cost savings. Filament winding, automated tape laying, robotics, and other techniques are being thoroughly examined for their particular role in the marketplace. Filament winding offers a number of advantages over other manufacturing techniques.

Continuous filaments are the cheapest and strongest form of fiber reinforcement. These fibers can be oriented to match the direction and magnitude of stresses in a structure, allowing reinforcement loading (Fig. 1). In addition, automating the application of reinforcements assures low labor costs, increases reproducibility, and helps reduce scrap rates.

There are also several disadvantages to filament winding. It is limited to those products with suitable outer contours; the outer surface often has to be accepted in an as-wound condition; and, if required, mandrel removal from a closed-end winding is difficult or impossible.

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metal vessel (both hoop-wrapped and fully wrapped hoop and helical vessels). Designs are established by using analyses combining strength and strain characteristics of filament and metal shells. This concept, with the load-bearing metal liner, is referred to as a filament-reinforced metal pressure vessel. A computer program using the netting analysis method was developed by Aerojet Corporation [1] to perform calculations for the design and structural analysis of pressure vessels fabricated from filament-reinforced metal shells. Most current application tanks are of this type because of their requirements for low development cost and high cyclic life capability.

In the second design approach, filament windings are used to reinforce a very thin metal liner having the minimum possible thickness required for impermeability and fabrication. The liner carries only a small share of the structural load. Liners used are low-strength ductile metals such as aluminum, stainless steel, and titanium. This concept, with the liner carrying only a small share of the load, is referred to as a metal-lined filament-wound pressure vessel. NASTRAN is the most popular analysis program.

Computerized design analysis of composite pressure vessels considers the strength and deformation characteristics of the internal metal liners including plastic deformation and the external reinforcing filament/resin structures. Safe life-cycle fatigue and static loading stress levels are selected for both the metal liner and the overwrap based on specified service life requirements. These levels are used to establish required material thicknesses and the resulting pressure vessel burst strength. The internal metal liner is designed to be the weak link in cyclic fatigue. The overwrapped filament/resin structure is made to be the primary load-carrying shell with a high factor of safety in burst and fatigue and with a thickness adequate to allow for normal abuse and cut surface fibers. Thus, if a fully wrapped composite cylinder is cycled to the point of final failure, crack growth through the metal liner results in leakage and loss of pressurized gas without rupture. Fig. 2 shows a typical metal-lined composite pressure vessel.

For nonmetallic liner design, the most important aspect is the method of end attachment. Highly loaded parts may require wound-in metal bosses to react to and distribute loads. The boss can be wound into the laminate to provide threads, attach points, and pressure ports. The boss is usually separated from the composite dome with an elastomeric washer to allow differential movement between the composite and boss without introducing local stress concentration. Motor cases usually require detailed finite element analysis, in which each load case needs to be considered. The critical interfaces between the composite joint, stiffening ring, and boss attachment flange require special attention and careful analysis.

3. Winding machine considerations

In choosing the appropriate filament winding machine, the user must first evaluate the part to be wound. Depending on the curing method, the filament winding machine may require the largest equipment capital expenditure. It is very important to maximize the output of the filament winder. To do this, it is critical that all mandrel and post-winding preparations are done away from the winder. In choosing a filament winding machine, the user must also evaluate the diameter, length, and weight of the part to be wound. In addition, the sophistication of the part will also help determine the equipment needed. How many axes are required to wind the part to your specification? If the part can be wound with only two axes, it may be possible to use a machine with an inexpensive two-axis control. If more than two axes are required, a more sophisticated, computerized winder should be used. In addition, the fibers may not spread out properly through the linear section depending on the delivery eye used. To help with the band placement, an eye rotation axis can be added. If the diameter of the part changes or the fiber build-up is significant, a cross-feed axis for in and out motion may be added.

Automation Dynamics, Inc., in Signal Hill, California, is a US company offering both mechanical and computer-controlled multi-axis winding machines. Fig. 3 shows a typical two-spindle, mechanically controlled helical filament winding machine.

4. Tooling considerations

One reason for the popularity of filament winding as a manufacturing technique for composites is tooling simplicity.
The male mandrel that provides the part with its internal geometry is usually the only major tool. Several considerations should be noted when designing mandrels: (i) a steel mandrel should be chosen over aluminum for removable mandrels because it is wear resistant and has a lower coefficient of thermal expansion; thus a precision ground steel mandrel is ideal; (ii) for parts that are wound at low fiber angles, pin rings at the mandrel ends may be required to prevent the fiber from slipping; (iii) molds for dissolvable mandrels must account for thermal expansion to produce the desired mandrel dimensions at room temperature; (iv) a rubber liner may be cast in the mandrel mold or bonded in place on an already cast mandrel. Pressure vessels and rocket motor cases require reduced openings on the ends. For these parts, a mandrel is used that can be dissolved, removed through an end opening, or left with the part.

For most pressure-vessel applications, a liner is needed inside the part to prevent the high-pressure gas or liquid from leaking through the composite wall. The liner may be plastic, metal, or rubber. Rigid liners are designed to support fiber tension during filament winding. Rubber-lined vessels require a dissolvable material such as sand, plaster, eutectic salt, foam, or low-melting-point alloy to support the rubber liner during the winding operation.

Collapsible mandrels are used on motor cases with large port openings or used to obtain high quality, high production motor cases or for both horizontal and vertical applications. Sand mandrels are usually used primarily for small- and medium-size motor cases and can be used on Independent Research and Development (IR&D) programs. They are ideally suited for high quality, high production cases and are typically used in vertical winding operations. The advantages of a sand mandrel are that it is easy to wash out after case fabrication, provides good contour tolerance control, promises low production cost, and requires minimum maintenance. The disadvantages are insulator contamination and that sand mandrels are very heavy and are limited to vertical winding operations. It is a major tooling modification to change contours and is also a relatively dirty, messy operation. Plaster or wood-reinforced mandrels are used primarily for medium- and large-size cases with large port openings and are suited to both horizontal and vertical winding applications.

The second option involves the spin closing of extruded tubes without a drawing operation. The finished liner is then heat treated and machined to the required thread size for the attachment.

Liners fabricated with other metals are usually formed components such as domes, polar fittings, and cylindrical sections. They are welded together and then heat treated.

6. Winding pattern

Filament-wound products are produced by using one of the three basic types of winding patterns: polar, helical, and hoop. The choices made are based on the shape of the part and the reinforcement orientations required. Polar winding is used to lay down fiber close to 0° to the longitudinal axis. Polar windings generally pass close to or around the mandrel poles. Each completed polar winding pattern covers the mandrel surface with a single layer of reinforcements (Fig. 5). Helical winding is used to lay fiber at angles from 5° to 80° to the longitudinal axis. These fibers are wound on the mandrel surface in alternating positive and negative orientations and result in a double layer of wound material. Helical windings may pass around the end of a closed-end shape (Fig. 6).

Hoop winding is a special form of helical winding and is used to deposit fiber close to 90° to the longitudinal axis. Hoop windings are generally applied only to the cylindrical or straight portion of a mandrel and result in a single layer of reinforcement material (Fig. 7).

5. Metal liner fabrication

The most commonly used liner material in the industry is aluminum 6061. Fabrication of this type of liner is either by deep draw and spinning or by extruded tubing and spin closing. The first option is a multistep operation with intermediate anneals. The aluminum liner starts as a large circular plate with zero condition that is progressively shaped and drawn using dies of various sizes. The process takes several draws, with quality checks after each operation. The open-end shell is then heated and closed by a computer-assisted spinning process, creating the neck and shoulder of the liner (Fig. 4).
7. Manufacturing considerations

Because many process variables are involved, filament winding time may involve several trial-and-error operations. Assumptions to be made include bandwidth, material wetout, machine speeds, angle of placement, and operator skill. Proper bandwidth placement and machine speed can influence the winding time. Because of these process variables, a sample winding should be completed to help determine an accurate time estimate. Mandrel handling will depend largely upon the actual part and mandrel weight. The mandrel handling can be as simple as two operators unchucking the mandrel and carrying it to the next station or as elaborate as a fully automated conveyor with no operator intervention. Another alternative is to use a cart system with rollers to transport the mandrel. The cart supports that hold the mandrel could be free-turning in bearings, allowing the mandrel to be wound while on the cart. Depending on the resin system, it may be possible to cure the part at room temperature. The only requirement for the cure station would be the turning station. Rotating the part while it cures gives it an even resin content. If the part is not rotated, the bottom may end up resin rich while the top is light on resin. If the resin system used requires additional curing heat, several techniques are readily available. Depending on the heat requirements, there are infrared and rollup heaters or a complete oven system with a means for rotating the part while it is in the cure cycle. Autoclave curing is not usually required for this kind of product.

8. Inspection and certification

Composite cylinders, used in interstate commerce, are subject to the regulations of the US Department of Transportation (DOT), Hazardous Materials Regulation Office. Design, material, manufacture, inspection, and test requirements for metal cylinders are specified in Title 49 CFR. However, there are no such specifications for composite cylinders. Their uses are authorized by ‘Exemptions’ to the specifications for individual companies. In 1976, the first DOT exemption was issued to Structural Composites Industries (SCI), Pomona, California, for a fully wound composite pressure vessel [2]. Since then, several other companies have obtained exemptions. Currently, a standard FRP 1 has been published by the DOT for this type of product for design and development usage [3].

For commercial filament-wound composite pressure vessels, the DOT requires the following acceptance test for production units: (1) a 100% examination of the product and (2) a 100% proof pressure test. Also, to qualify a production lot of 200 units, destructive tests must be performed as follows: (1) one out of each 200-unit production lot for an ambient temperature cycling test and (2) a hydraulic burst test.

The qualification tests for a new design involve one hydraulic burst test, one ambient temperature cycling test, one environmental cycling test, one thermal cycling test, one gunfire test, and one bonfire test.

9. Applications

Filament-wound composite pressure vessels are being used for containment of gases/liquid in both aerospace and commercial applications. The following are a few examples: (1) for space applications, a propellant tank, engine purging, auxiliary power, astronaut life support, and cold gas thruster; (2) for aircraft and helicopter applications, inflation of emergency high-altitude gaseous oxygen, hydraulic accumulator, fire extinguisher, and pneumatic gun drive power and oxygen bottle for passenger use; (3) ground services such as emergency breathing apparatus for fire fighters, miners, and rescue workers; automotive fuel such as compressed natural gas; over-the-highway trailer tubes for industrial compressed gas; and medical compressed gas.
Fig. 8. Compressed natural gas bus.

One potentially large application is the compressed natural gas (CNG) vehicle (Fig. 8). The advantage of CNG over gasoline is that it carries higher octane. This means the end of engine knock, longer spark plug life, longer distance between oil changes, and instant winter startups. However, because of cost and safety issues, tanks used for this application most likely will be low cost fiberglass (E-glass) overwrapped on a load-sharing aluminum liner (6061) configuration.

10. Conclusions

Filament winding has been shown to have many useful and successful production applications. It is also a cost-effective automated means for depositing reinforcement materials in specifically oriented patterns. But it is a manufacturing method that is still unfamiliar to some people. High-modulus carbon fiber has opened another door for this product. It provides the highest-performance, lightest-weight fabrication materials for tankage operating at high pressures over a wide temperature range. Advanced composite pressure vessels are now being used for military, aerospace, and transportation uses because of their low cost, weight savings, and safety. New tooling and production concepts and programmable computer-controlled filament-winding machines are helping to expand the variety of parts that can be produced by this process.

References