COST COMPARISONS OF WET FILAMENT WINDING VERSUS PREPREG FILAMENT WINDING FOR TYPE II AND TYPE IV CNG CYLINDERS

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SUMMARY: This paper quantifies the significant cost elements for filament winding with wet resins and with pre-impregnated tow fibers. A detailed cost model is presented that calculates the total cost contribution for each winding approach. Two types of over-wrapped cylinders will be studied. Both Type II and Type IV CNG cylinders will be studied to select the most cost-effective approach of either wet winding or prepreg winding. A Type II CNG cylinder is a metal cylinder that is circumferentially wrapped with fiber tow over the straight cylindrical section. A Type IV CNG cylinder is a plastic cylinder that is fully over-wrapped with both circumferential and helical fiber tows.

A cost model with the detailed assumptions and data required for making valid cost comparisons between wet and prepreg filament winding will be presented. This model will be useful for making cost comparison for alternate materials and designs and will allow the user to make informed selections that will yield the most cost-effective approaches for typical CNG cylinders.

KEYWORDS: filament winding, compressed natural gas cylinders, wet filament winding, prepreg filament winding, cost comparisons

INTRODUCTION

Selecting the most cost-effective filament winding approach for the fabrication of CNG cylinders requires a detailed analysis of all aspects of the fabrication process. It is a lengthy task to identify all of the elements of cost that affect the final item total cost. It is not adequate to consider only the direct labor and raw material costs. Issues such as manufacturing throughput, scrap, down time for cleanup, and the costs associated with being environmentally compliant all need to be considered for an accurate picture of the final item cost.

In this paper, two sample problems will be studied to highlight the variables that must be considered to make an informed choice between wet winding and prepreg winding. A Type II (Fig. 1) and a Type IV CNG cylinder (Fig. 2) will be used to illustrate the process of making realistic comparisons on cost. The reader is cautioned that the data and the assumptions made will not necessarily apply to all manufacturers. Due to the wide variations in cylinder designs, winding methods, and materials used, each manufacturer must collect his/her own data to make valid cost comparisons between wet winding and prepreg winding.

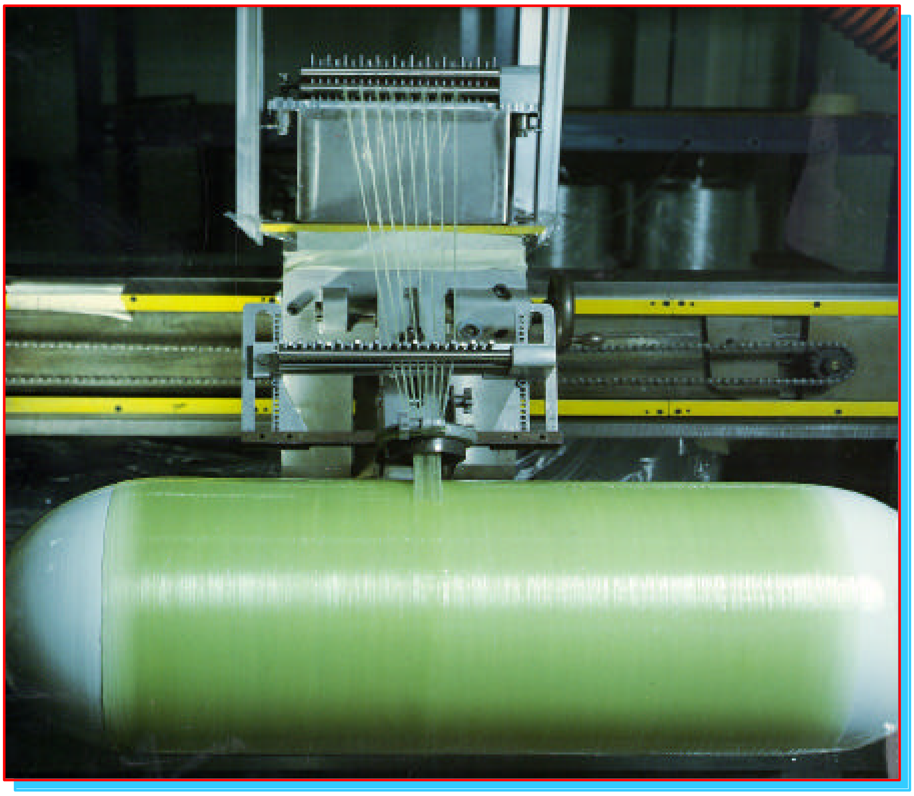

Fig. 1: Type II CNG Cylinder

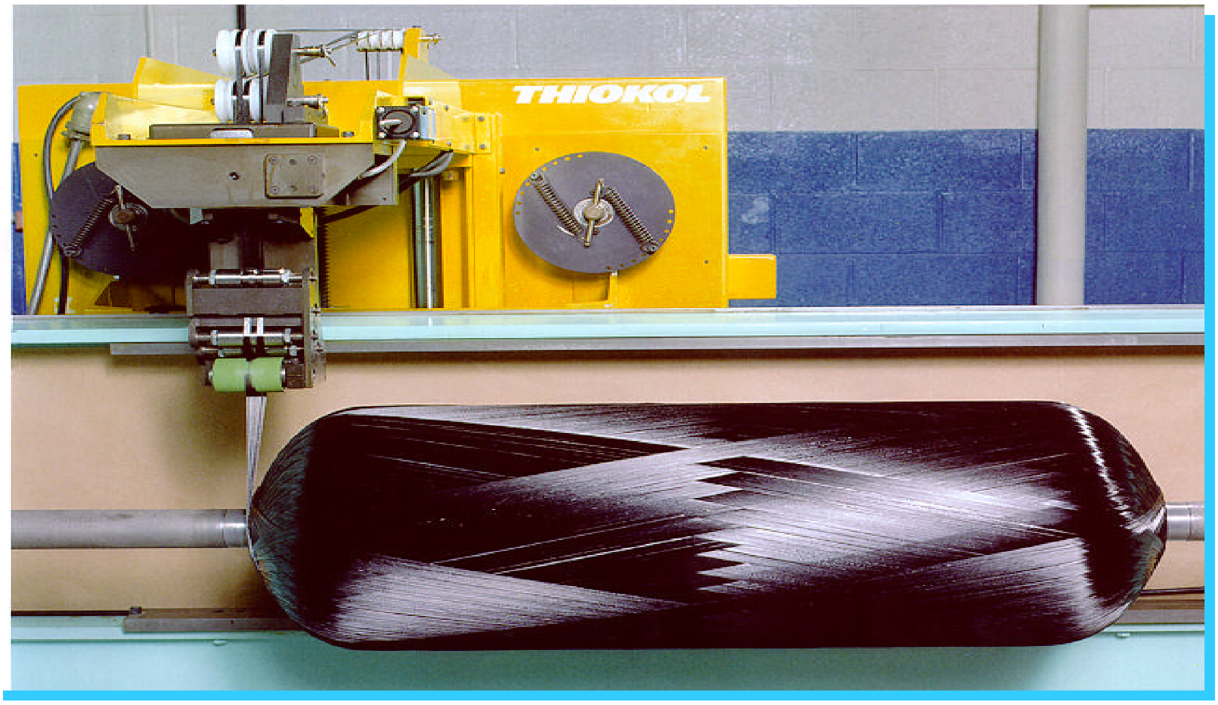

Fig. 2: Type IV CNG Cylinder

BODY OF THE PAPER

Background

Filament winding with prepreg tow offers advantages over wet winding for certain applications. Prepreg tow allows for more precise control of resin content, which yields less variability in the cured part mechanical properties. Depending on the application, prepreg tow winding will generally yield higher fiber delivery rates and therefore higher component production throughput. The capability for greater product throughput with prepreg when compared to wet winding can often justify the higher material cost of prepreg. Prepreg tow also provides advantages in allowing a much cleaner work place with significantly reduced environmental hazards for the operators. Prepreg has little to no emission of volatile off-gassing compounds (VOC's) and ozone depleting compounds (ODC's) and also does not expose operators to hazardous chemicals. The disadvantage of typical prepregs is that the raw material costs are higher than for wet winding materials. Typical prepregs also require refrigerated storage and have a relatively short out life at ambient temperatures. However, Thiokol has developed a family of prepreg materials that do not require refrigerated storage, and can be stored at ambient temperatures for a minimum of one year.

Wet resin filament winding offers the lowest raw material costs and the advantage of simplified material storage for the dry fiber and resin. However, fiber delivery speeds with wet winding are somewhat limited due to the time required to achieve good fiber/resin wet out. It is also more difficult to achieve precise resin content control with wet winding and therefore it will yield greater variability in cured part mechanical properties. Many components fabricated with wet winding will require a gel cycle prior to the final cure process on the part. This is necessary to prevent localized dripping or pooling of the resin during final cure. Prepregs typically do not have this problem. A gel cycle requirement adds time and expense to the overall manufacturing process. Wet winding also is a messy process that requires significant time and large quantities of solvent for cleanup. Also, the use of solvents requires additional effort in dealing with the environmental issues that are created. Wet winding also exposes the machine operators directly to hazardous chemicals and vapors.

CNG cylinders are high performance pressure vessels that are operated at relatively high pressures (3,000 psi). High reliability and repeatability are absolutely essential for this application. In addition, lightweight and long fatigue life are also required. If you couple these requirements with the need for low cost and high production rates, it becomes a very challenging manufacturing problem that demands the utmost performance from the liner and composite overwrap materials. Prepreg overwrap materials can offer a number of advantages for this application including: precise resin content control, fiber placement which eliminates slipping on the tangent line between the cylinder and the dome, high fiber delivery rates, little to no cleanup, and no environmental issues. For this application, failures can be catastrophic, therefore a consistent, repeatable, and controllable prepreg material can contribute to overall program success.

Raw Materials

In the case of a Type II or Type IV CNG cylinder, it will be assumed that the liner material and geometry will be identical. Therefore, the discussions and examples will focus on the costs associated with the composite overwrap and the differences in wet versus prepreg filament winding processing.

When utilizing wet winding it isn't uncommon to consider a slightly higher cured weight of the composite overwrap when compared to prepreg winding. When using prepreg material, the “as wound” weight of the composite is expected to be slightly less than is the case for a wet wound tank. This is due to the prepreg tow's tighter resin control that enables the overwrap weight to be controlled closer to nominal values. A two (2%) weight reduction for the prepreg overwrap is believed to be a realistic estimate.

The weight of resin used for wet winding is based on 32% resin content by weight to which must be added a 35% wastage factor. Wastage includes resin squeezed off during winding and curing, drips, spills, and any material discarded during resin bath changes and mixing. The wastage factor varies within a range of 20% to 50%. A wastage factor of 35% is considered to be an acceptable level for this analysis.

The weight of dry carbon fiber used per over-wrapped cylinder is considered to be essentially the same for wet winding or prepreg winding. There is a small amount of fiber that is wasted during machine set-up, on wet winding, and also a small amount of prepreg that is wasted at the end of the spool when the spool must be changed. The fiber weight is based on a 68% fiber content by weight in the cured overwrap.

Not all companies will use the same solvents for resin cleanup. For the purposes of this analysis it is assumed that acetone is the solvent that will be used for waste cleanup. Acetone currently is priced at approximately $300 per drum. Most of the acetone is lost by evaporation, with the contaminated remainder put into hazardous waste containers for subsequent removal by a hazardous waste management company. As a rule of thumb, one drum of hazardous waste is produced for every three of solvent used. This is an accepted ratio within the filament winding industry. The current price estimate for disposing of a drum of hazardous waste is $350 per drum.

The basic fiber, resin and prepreg tow cost data was provided by the TCR Composites Division of Thiokol and is applicable to all filament-winding companies. Most wet winding companies are using resin systems that are priced in the range of $3.50 to $4.25 per lb. Therefore this analysis uses $3.87 per lb as the cost of resin for wet winding.

AKZO-50K standard modulus fiber will be assumed for the Type II hoop wrapped cylinders. The current cost of AKZO-50K dry fiber is $9.75 per lb. The cost of prepreg made from this fiber is $13.50 per lb. These numbers will be assumed for the cost analysis of Type II hoop wrapped cylinders.

Toray M30S-18K intermediate modulus carbon fiber will be assumed for the Type IV fully over-wrapped cylinders. The current cost of M30S dry fiber is $29 per lb. The cost of prepreg made from the same fiber is running at $37 per lb. These are cost numbers that will be assumed in all analytical cost model predictions for Type IV cylinders.

Equipment, Labor, and Wage Rates

For this study it is assumed that one three spindle-winding machine is available for manufacturing over-wrapped CNG cylinders by either wet winding or prepreg winding. In the case of wet winding, it will require one full time skilled winding technician and an one full time assistant to help with mandrel setup, fiber spool up, resin mixing, resin bath setup/change out, management of excess resin dripping during the winding process, removal of fiber fuzz accumulation, and removal of completed cylinders.

In the case of prepreg winding, one full time skilled winding technician will be required, but only one-fourth time support from an assistant to help with mandrel setup, prepreg spool setup/change out, and removal of completed cylinders.

The hourly wage rate for a skilled winding technician was assumed at $45.00 per hour, and a winding assistant at $35.00 per hour. These are both fully burdened labor rates representative of a typical commercial filament winding operation.

Downtime, Productivity, and Scrap

Most winding companies believe that when wet winding, about 0.5 hours per shift is devoted to setting up the filament winding machine and any subsequent cleaning of the equipment. The machine downtime is minimized by replacing a "dirty" resin bath with a fresh one, and then cleaning it elsewhere in the factory. There is some minimal equipment cleanup required with prepreg (such as guides/rollers) although this is judged to be minimal compared to wet winding. In any case there remains a 0.5-hour differential in useable machine time per shift between wet winding and prepreg winding.

Most companies believe that winding with prepreg tow allows for greater winding speeds and therefore the production of more units per shift than with wet winding. Opinions vary widely on just how much this throughput advantage is. In any case, opinions vary from 10% to 80% throughput advantage with prepreg. This study will assume an average value of 50%. There are no absolutes on this subject, due to great differences in winding methods. This is a key parameter in making cost comparisons between wet and prepreg winding. **It is essential that each manufacturer conduct winding trials to quantify this number to their own level of satisfaction.**

On the subject of finished cylinder scrap, wet winding does have a higher variability of resin content in the cured part. If it is on the high side, the component will have a greater weight and may be rejected on the basis of not meeting the tank weight requirement. If the resin content is on the low side, the mechanical properties of the overwrap may be inferior and the tank could fail during proof test. Since prepreg has a much narrower variability on resin content, tanks over-wrapped with prepreg are less likely to be rejected for either of the above reasons. Based on this discussion, an overall scrap rate of 10% will be used for wet winding and 2% for prepreg winding.

Testing and Other Production Costs

For this analysis, the cost of proof testing, painting, printing/applying labels and packaging, is assumed to be the same for both wet wound and prepreg wound cylinders. An average value of $50.00 per cylinder has been used in the analysis.

Financial Analysis of a Type II Hoop Wrapped Cylinder

Table 1 illustrates all the data items that were discussed above and the required calculations to make a comparison of wet winding versus prepreg winding for a hoop wrapped Type II cylinder that is 16 inches in diameter and 50 inches in length. The calculated total unit costs of manufacturing hoop wound cylinders using the two production methods are shown in Table 1. There is approximately a $52.50 per cylinder difference in favor of wet winding. As expected, labor costs are lower but material cost is higher for prepreg winding. However, if the profitability over a fixed period of time (one month) is considered, then prepreg will contribute an additional $9,000 per month when compared to wet winding**,** because of the significantly greater throughput that is achieved. This is particularly significant for companies that have capacity restrictions.

Financial Analysis of a Type IV Fully Over-wrapped Cylinder

Table 2 illustrates the data and calculations required to make a comparison of wet winding versus prepreg winding for a Type IV fully over-wrapped cylinder that is 12 inches in diameter and 37 inches in length. The calculated total unit costs of manufacturing fully over-wrapped cylinders using the two production methods are shown in Table 2. There is approximately a $237.64 per cylinder difference in favor of wet winding. Again, as in the case of a hoop wrapped Type II cylinder, the labor costs are lower, but material cost is higher for prepreg winding. However, if the profitability over a fixed period of time (one month) is considered, then prepreg will contribute a small additional amount of $1,932 per month over wet winding due to the greater throughput that is achieved.

CONCLUSIONS

Both of the sample problems outlined above are considered to be representative of the type of processes that Thiokol uses. However, each manufacturer will be required to collect their own data and perform similar calculations to make an informed decision relative to the choice of prepreg or wet winding. It is also important to consider the impact of unit to unit variability, environmental issues, scrap, and winding operator health concerns when comparing wet winding to prepreg winding.

Table 1: Wet Winding versus Prepreg Winding Cost Model
Hoop Wrapped Type II Cylinder (16 in. dia. X 50 in. length)

Data Items	**Wet Winding**	**Prepreg Winding**
Weight of cured overwrap	18.97	18.60
Weight of resin used per cylinder	8.20	
Weight of fiber used per blank (lbs)	12.65	
Weight of prepreg used per blank (lbs)		18.70
Drums of solvent used per 150 cylinders	3	
Drums of hazardous waste per 150 cylinders	1	0.1
Cost of fiber ($/lb)	9.75	
Cost of resin ($/lb)	3.87	
Cost of solvent ($/drum)	300.00	
Cost of prepreg ($/lb)		13.50
Cost of waste removal / drum ($)	350.00	350.00
Number of 3 spindle winders	1	1
Number of skilled winders required	1	1
Number of assistant winders required	1	0.25
Hourly wage rate of skilled winder (with benefits)	45.00	45.00
Hourly wage rate of assistant winder (with benefits	35.00	35.00
Downtime / shift for resin bath & machine cleaning (hrs)	0.5	
Number of cylinders produced per hour per 3 spindle winder	1.2	1.8
Cylinders scrapped (%)	10	2
Cost of prepreg per cylinder		252.45
Cost of resin per cylinder	31.73	
Cost of fiber used per cylinder	123.34	
Cost of solvent used per cylinder	6.00	
Cost of hazardous waste removal per cylinder	2.33	0.23
Labor costs per wet wound cylinder	66.67	
Labor costs per prepreg wound cylinder		29.86
Cost of testing, finishing, and packaging per cylinder	50.00	50.00
Manufacturing overhead per cylinder	175.00	175.00
Total cost of wet wound cylinder	455.07	
Total cost of prepreg wound cylinder		507.54
Average selling price per cylinder	610.00	610.00
Quantity of cylinders manufactured per month	180	288
Quantity of cylinders available for sale per month	162	282
Sales value per month (WET)	98,820.00	
Sales value per month (PREPREG)		172,166.40
Monthly sales	98,820.00	172,166.40
Cost of sales (WET WINDING)	81,912.87	
Cost of sales (PREPREG WINDING)		146,172.80
Monthly contribution to fixed cost & profit (WET)	16,907.13	
Monthly contribution to fixed cost & profit (PREPREG)		25,993.60

Table 2: Wet Winding versus Prepreg Winding Cost Model
Fully Overwrapped Type IV Cylinder (12 in. dia. X 37 in. length)

Data Items	**Wet Winding**	**Prepreg Winding**
Weight of cured overwrap	17.85	17.50
Weight of resin used per cylinder	7.71	
Weight of fiber used per blank (lbs)	12.14	
Weight of prepreg used per blank (lbs)		17.56
Drums of solvent used per 150 cylinders	3	
Drums of hazardous waste per 150 cylinders	1	0.1
Cost of fiber ($/lb)	29.00	
Cost of resin ($/lb)	3.87	
Cost of solvent ($/drum)	300.00	
Cost of prepreg ($/lb)		37.00
Cost of waste removal / drum ($)	350.00	350.00
Number of 3 spindle winders	1	1
Number of skilled winders required	1	1
Number of assistant winders required	1	0.25
Hourly wage rate of skilled winder (with benefits)	45.00	45.00
Hourly wage rate of assistant winder (with benefits	35.00	35.00
Downtime / shift for resin bath & machine cleaning (hrs)	0.50	
Number of cylinders produced per hour per 3 spindle winder	2	3
Cylinders scrapped (%)	10	2
Cost of prepreg per cylinder		649.72
Cost of resin per cylinder	29.84	
Cost of fiber used per cylinder	352.06	
Cost of solvent used per cylinder	6.00	
Cost of hazardous waste removal per cylinder	2.33	0.23
Labor costs per wet wound cylinder	40.00	
Labor costs per prepreg wound cylinder		17.92
Cost of testing, finishing, and packaging per cylinder	50.00	50.00
Manufacturing overhead per cylinder	100.00	100.00
Total cost of wet wound cylinder	580.23	
Total cost of prepreg wound cylinder		817.87
Average selling price per cylinder	1,100.00	1,100.00
Quantity of cylinders manufactured per month	300	480
Quantity of cylinders available for sale per month	270	470
Sales value per month (WET)	297,000.00	
Sales value per month (PREPREG)		517,440.00
Monthly sales	297,000.00	517,440.00
Cost of sales (WET WINDING)	174,069.31	
Cost of sales (PREPREG WINDING)		392,577.60
Monthly contribution to fixed cost & profit (WET)	122,930.69	
Monthly contribution to fixed cost & profit (PREPREG)		124,862.40

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