FABRICATION OF A RECYCLED TOW CARBON FIBER OVERWRAPPED PRESSURE VESSEL

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Abstract

Steelhead Composites, in partnership with Vartega and Michelman, created the first composite overwrapped pressure vessel (COPV) manufactured from continuous recycled carbon fiber tow. Recycled carbon fiber has typically been downcycled as chopped fiber or filler. This demonstration suggests that there may be additional utility in maintaining original product form.

The COPV was fabricated by overwrapping an aluminum vessel with recycled continuous carbon fiber tow. The fiber was recycled with Vartega Inc's proprietary process, and was sized by Michelman. This collaboration marks the first time that continuous carbon fiber scrap has been reclaimed, recycled, and put back into the original COPV manufacturing process.

The recycled fibers and vessel were destructively tested and compared to virgin materials.

Introduction

Fiber reinforced composites present unique sustainability challenges for manufacturers. Manufacturing scrap rates tend to be high due to product expiration, unusable "end-of-roll" segments, and high percent remnants when cutting from prepreg. As fibers cannot be melted and reformed for drop-in material in a manner similar to metals, much of this material is landfilled rather than recycled. Industry has sought means of recovering and reusing material, but many applications involve downcycling as filler or other low-value product. More value may be recovered with the utilization of chopped recycled fibers in compounding applications or through preserving fiber product form for creation of drop-in replacement product.

Composite Overwrapped Pressure Vessels (COPVs) are increasingly utilized in weight sensitive applications, specifically mobile terrestrial applications. Carbon fiber provides a much higher specific strength than steel for pressure vessels, allowing COPVs to be up to 75 percent lighter than their steel counterparts with properly engineered carbon fiber overwrap design. This weight savings allows for easier maintenance, installation, increased payload, better fuel economy, and reduced operating costs. Steelhead Composites supplies composite accumulators to Lightning Systems, who utilizes these accumulators in their hydraulic hybrid drive systems for medium duty trucks to improve fuel efficiency and reduce emissions. The motivations for increased fuel economy are both financial and regulatory. Steelhead's accumulators are also used to reduce weight in subsea, oil and gas, off-road vehicle, high-performance automotive, robotic, and aviation applications. The weight savings of COPVs do come at a price, which can vary greatly depending on application. Small vessels (under five liters) can cost two to twenty times more than similarly rated steel vessels. However, large COPVs (over 30 gallons) can approach cost parity or savings over their steel equivalents due to the costs of handling such a large amount of steel. As the COPV market increases, so will the manufacturing byproducts and

the need to recycle those byproducts.

The purpose of this demonstration was to evaluate recycled material in an application and product form similar to that of virgin material. A pressure vessel application provides an excellent practical comparison, as hydrostatic stresses are well-understood and virgin product test data is readily available.

Recycling and Winding Process

Approximately 400 meters of continuous resin-impregnated tow was recycled using a proprietary extraction and cleaning process and rewound onto six partial spools, three shown in **Figure 1**. Michelman sized approximately 200 meters of the resulting dry fibers with an epoxy compatible sizing by passing the continuous fiber through a sizing bath. A sizing is a mixture of various chemicals, typically (but not necessarily) diluted in water, that fiber and fabric producers use to coat ('size') their fibers. As demonstrated in this project, sizing plays an important role in the protection and processability of the fibers. Furthermore, appropriate selection of sizing helps improve the interfacial adhesion between the fibers and the matrix resin, thus allowing for efficient load transfer ultimately leading to enhanced mechanical properties. Michelman develops custom sizings for various fibers and resin matrices for applications ranging from automotive, sports, textiles to high performance aerospace applications. A sizing weight percent of approximately 6.7% was determined through thermogravimetric analysis (TGA) using a TA instrument <TA 850> and soxhlet extraction. A comparison between the re-sized and unsized recycled fiber clearly demonstrates the effect of sizing as shown in **Figure 2**. The re-sized fiber exhibits minimal fraying.

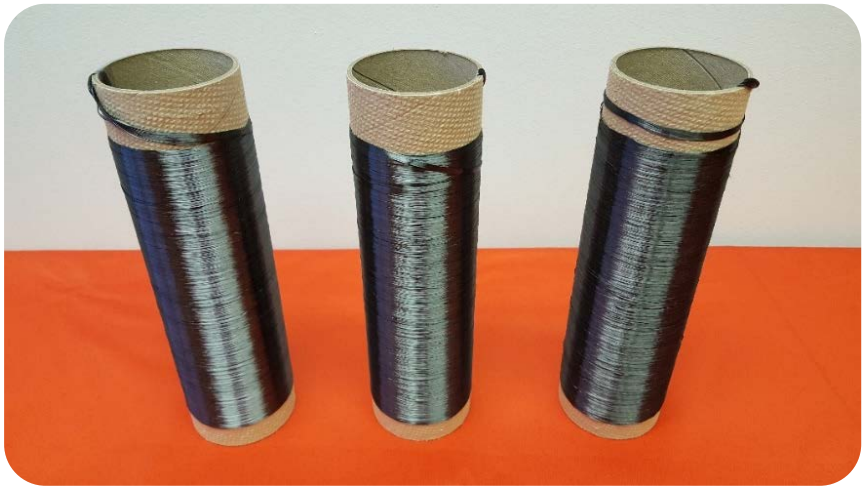

Figure 1: Recycled carbon fiber spools

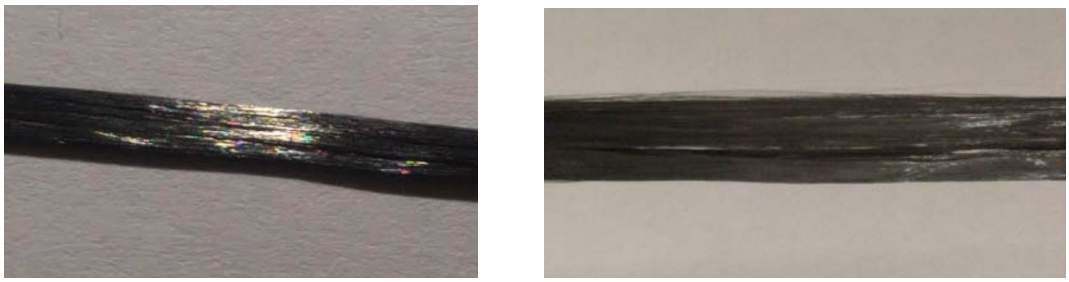

Figure 2: Sized (left) and unsized (right) recycled continuous fibers

Three spools of continuous dry fiber were provided to Steelhead composites for a wet winding process. However, without sizing, individual dry fibers tended to fray at filament winding machine touchpoints. This attrition initiated upstream of the wet-winding resin bath. While equipment reconfiguration to remove those touchpoints would reduce fiber attrition, schedule limitations made this impractical and the winding process for unsized fibers was abandoned.

The sized material rolls were wet wound in the same equipment and configuration as the dry fiber, but showed negligible material attrition; the applied sizing was effective at protecting the continuous fiber as it traversed equipment touchpoints. The fiber was passed through an epoxy resin bath and successfully overwrapped on a 450cc aluminum vessel. The recycled fibers were wound using the same pattern as the towpreg-based commercial version of the product. The completed vessel is shown in **Figure 3**.

Figure 3: Recycled carbon fiber overwrapped pressure vessel

Testing

Vartega's recycled carbon fiber was evaluated by an independent third party and mechanical property testing was performed by SGL according to ASTM D4018 and compared to a control.[1] As summarized in **Table I**, measured recycled fiber sample mechanical properties are similar to that of control and published data[2].

Table I: ASTM D4018 Test Results

Sample	Tensile Strength (MPa)	Modulus (GPa)	Elongation (strain %)
Manufacturer Data	4900	230	2.1
Control Sample	5066	221	2.05
Recycled Sample	5134	225	2.10

A hydrostatic burst test (**Figure 4**) on the completed carbon fiber overwrapped pressure vessel resulted in a rupture at 737 bar. Burst pressure was measured using calibrated digital pressure transducers with a range of 0 to 2068 bar with 10 Hz sampling. This result was 87% of the average burst pressure for the virgin towpreg equivalent of that vessel design, but met the manufacturer pass criterion of 724 bar. Given that ASTM D4018 testing does not indicate fiber degradation during recycling, the following may form the bases of the variation from average:

- Fiber breakage during re-winding or re-sizing.
- Suboptimal winding pattern for wet-winding.
- Variations between wet-wound and towpreg-based vessels.

Figure 4: Burst Recycled pressure vessel (737 bar)

[1] ASTM D4018, Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows
[2] Technical Data Sheet No. CFA-005, Toray Carbon Fibers America, Inc.

Conclusions

A carbon fiber overwrapped demonstration vessel was successfully wet-wound with recycled and re-sized continuous carbon fiber tow. The vessel burst at a manufacturer acceptable pressure, albeit one reduced relative to average for standard virgin towpreg-wound equivalents. Additional testing may be performed to identify and characterize any mechanical difference between virgin and recycled material. Continued process refinement and testing would be required to establish constraints (continuous length, etc.) on the recycling process used in this demonstration. Follow-on projects to create recycled towpreg may present additional commercial applications.