Metal Prepreg Filament Winding

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Abstract

MetPreg™ is a technology in which fiber reinforced metals are produced using all the traditional composite processing techniques such as pultrusion, filament winding, tape placement, hot pressing, and vacuum bagging. This work is significant for applications where the high specific properties and temperature capability of metal matrix composites provide benefits over conventional monolithic metals and organic composites. Touchstone's metal matrix composite (MMC) technology has advanced significantly in the area of filament winding. Hydrostatic burst testing has been conducted on cylinders produced with both hoop and helical plies under conditions that produce a biaxial stress state in the cylinder wall. This testing will lead to the development and refinement of predictive models that can be used for designing optimized pressure vessels and other types of containers. For example, the combination of high strength and low permeability of MMC materials makes them good candidates for storing hydrogen for the new hydrogen-based economy. The MMC filament winding process is being scaled up for producing larger cylindrical sections, and future modifications will improve current end dome capabilities. This paper describes Touchstone's recent efforts to advance this unique technology.

Introduction

Metal matrix composites (MMCs) consist of a metal or metallic alloy matrix reinforced by whiskers, particulates, filaments, or wires of another material. The advantages of MMCs over monolithic metals are higher specific strength (strength-to-density ratio) and specific stiffness (stiffness-to-density ratio), improved fatigue and wear resistance, better mechanical properties at elevated temperatures, and tailorable coefficients of thermal expansion. Compared to polymer matrix composites (PMCs), MMCs have better fire resistance and high-temperature properties, greater transverse stiffness and strength, no moisture absorption or outgassing, higher electrical and thermal conductivities, and higher radiation resistance. Touchstone Research Laboratory has been working to establish renewed interest in continuous fiber MMCs by utilizing PMC manufacturing processes and existing PMC manufacturing expertise and equipment. This approach would overcome the cost and producibility barriers that steered past users away from continuous fiber MMCs and provide an economical means of utilizing the beneficial aspects of these materials.

The term "metal prepreg" has been coined as a means of conveying the concept at the heart of this technical approach. A metal prepreg is similar to other composite prepregs in that it is a ready-to-use material consisting of unidirectional fibers in a metal matrix from which finished parts can be fabricated with the addition of heat and pressure. Touchstone has given this technology the trade name MetPreg™. Metal prepregs enable the production of fiber reinforced metal components using traditional composite processing techniques such as pultrusion, filament winding, tape placement, hot pressing, and vacuum bagging. This paper describes Touchstone's current efforts to develop a filament winding technology for MMCs. Filament winding combines the MetPreg tape pultrusion process, which has been reported on in the past, with a filament winder to lay down an infiltrated fiber bundle onto a mandrel. This process will allow for the production of MMC pressure vessels, storage tanks, and other filament wound structures.

Experimental

Materials

The filament winding process has focused primarily on the composite system consisting of pure aluminum reinforced with continuous alumina fibers. Similar to the prepreg process, it is also possible to make use of a range of aluminum alloy matrices for filament winding. Heat

Table 1. Pure aluminum typical properties (annealed).

Property	Units	Value
Chemical Composition	wt. %	99.999+ Al
Melting Point	°C °F	660 1220
Density	g/cm^3	2.7
Tensile Strength	MPa ksi	40-50 6-7
Yield Strength	MPa ksi	15-20 2-3
Elastic Modulus	GPa Msi	62 9
Elongation	%	50-70
Thermal Expansion (25-600°C)	ppm/°C	25

Table 2. Nextel™ 610 ceramic fiber typical properties.

Property	Units	Value
Chemical Composition	wt. %	>99 Al_2O_3
Melting Point	°C °F	2000 3632
Filament Diameter	μm	10-12
Crystal Phase		α- Al_2O_3
Density	g/cm^3	3.9
Filament Tensile Strength (25.4 mm gauge)	Mpa ksi	3100 450
Filament Tensile Modulus	GPa Msi	380 55
Thermal Expansion (100-1100°C)	ppm/°C	8.0

treatable alloys such as the 2*xxx*, 6*xxx*, and 7*xxx* series can be incorporated into filament wound components. Generally, heat treatable alloys significantly strengthen the matrix, which substantially increases the shear strength, but can reduce the composite tensile strength due to local load-sharing phenomena. The increased shear properties of the matrix also lead to a higher compressive strength, much higher than that which can be achieved by organic composite materials. Proper selection of matrix material gives the designer the flexibility to tailor the mechanical properties of the laminate, which would be beneficial for a wide range of specific applications. Table 1 shows typical properties of pure aluminum in the annealed state.

Aluminum oxide (α-Al_2O_3) fibers are used effectively as high-strength, high-modulus reinforcement in aluminum-based MMCs (Deve, 1995). Nextel 610™ fibers were used for the data obtained under this study. Table 2 shows the pertinent fiber properties.

Other fiber types may be used depending on the strength and stiffness requirements of the finished component.

Filament Winding Process

The filament winding process is a method of achieving high-speed, precise lay-down of continuous reinforcement in prescribed patterns. Pressure vessels and other types of containers are routinely produced this way, with one example shown in Figure 1.

Some claim that filament winding is the oldest manufacturing process employed in the composites industry. The process consists of pulling a roving or tow (a bundle of fibers or filaments) through the matrix material in a liquefied form (for example, a resin bath), impregnating or infiltrating the roving material with the matrix material, and "wrapping" the impregnated roving over a mandrel. Filament winding is considered to be a very robust, inexpensive means of creating large, high-fiber-volume composite structures.

Despite the tremendous potential of continuous fiber reinforced MMC materials, adoption of MMC technology into applications has been slow for several reasons, including high relative cost, inconsistent material properties, immaturity of production processes, and the lack of a reasonably large production base. Filament winding has been around for decades, but no attempts to filament wind MMCs have ever been made. The confluence of these two diverse technologies, namely a low-cost filament winding process with high-performance MMC materials, can lead to great improvements in the ability to produce affordable MMC structures by driving down costs and improving manufacturing capabilities.

Filament winding of MMC cylinders and other shapes can be accomplished in the same manner as described above. The resin, of course, must be replaced with aluminum, and the aluminum must be kept molten. The way the infiltrated fiber bundle is laid down and the build-up of plies to form the desired laminate are completely analogous to a PMC wet filament winding process.

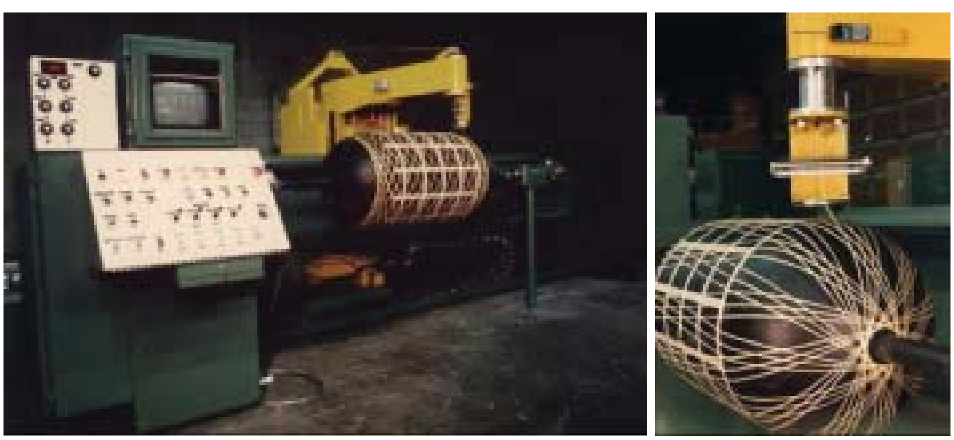

Figure 1. Composite filament winding.

Test Specimens

Cylinders have been produced using the MMC filament winding process as a means of determining the basic as-wound materials properties. Specific properties of interest include longitudinal, transverse, and shear strengths and stiffnesses. Cylindrical test specimens with an inner radius of 10 cm (4 inches) and length of 15 cm (6 inches) are used for testing purposes. The cylinder wall thickness varies depending on the type of test specimen being produced.

Figure 2. Uniaxial hydrostatic burst test fixture.

Test Fixtures

Specialized test fixtures were designed and built for performing tensile, shear, and hydrostatic burst tests for this effort. Fixture design varied depending on the type of test and required stress state in the test specimen. For example, pressurizing a cylinder with supported end closures develops only hoop stresses, whereas pressurizing a cylinder with attached end closures allows the development of hoop and axial stresses. In subsequent sections the former stress state is referred to as uniaxial and the latter as biaxial. The fixture for performing uniaxial hydrostatic burst testing is shown in Figure 2.

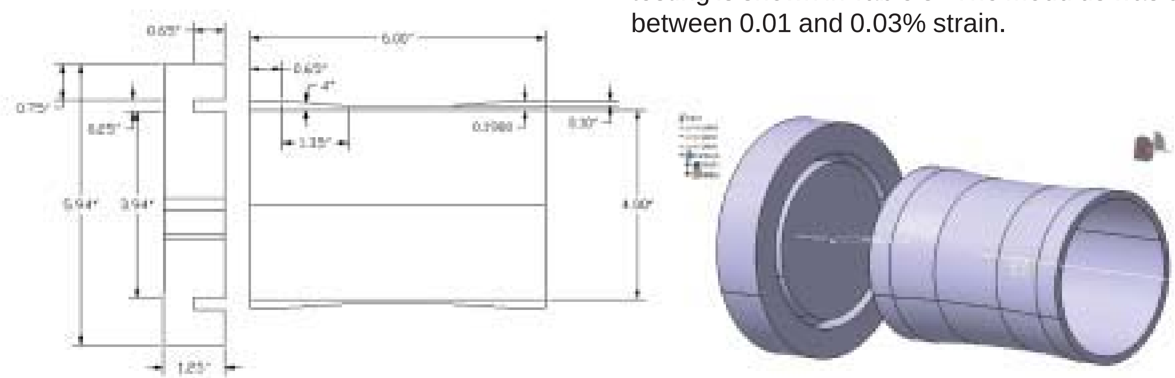

Figure 3. End closures for biaxial burst tests.

Bonded-on end closures are used for performing axial tension testing, torsion testing, and biaxial burst testing. The closures were designed to ensure that failure of the test specimen occurred in the gage section and not at the joint between the test specimen and the closure. The end closures for the axial tensile and torsion tests were aluminum plates with a groove cut-out for bonding. The closure design for the biaxial hydrostatic burst test was similar to those used for the tension and torsion tests but also included built-up end regions on the test cylinder to ensure that the break occurred in the center section of the cylinder instead of near the ends where the helical ply angle was varying in the turn-around zones. Figure 3 shows the closure design chosen for the biaxial burst testing.

As can be seen in Figure 3, the cylinder ends were made slightly thicker in order to force the failure location to the center of the cylinder. This build-up at the ends was achieved by wrapping multiple layers of a PMC prepreg over the ends of the MMC cylinder and curing. Figure 4 shows a test cylinder with over-wrapped ends and bonded-on end caps.

Results and Discussion

Tension Test Results

Tension tests were conducted on filament wound cylinders in order to determine the transverse properties of the material. These tests were performed on a tensile test frame with real-time collection of stress and strain data. The stress-strain curves for the samples tested are shown in Figure 5. There is significant non-linearity in the transverse tensile response.

A tabulated summary of the results from the axial tension testing is shown in Table 3. The modulus was calculated between 0.01 and 0.03% strain.

Figure 4. Test specimen for biaxial hydroburst testing.

Torsion Test Results

Torsion tests were conducted on filament wound cylinders in order to determine the shear properties of the material. These tests were also performed on a tensile test frame with special grips for applying torsional loading. Stress and strain data were again collected real-time and are shown in Figure 6. A significant non-linear effect is also present in the shear response.

A tabulated summary of the results from the torsion testing is shown in Table 4. The modulus was calculated between 0.03 and 0.05% shear strain.

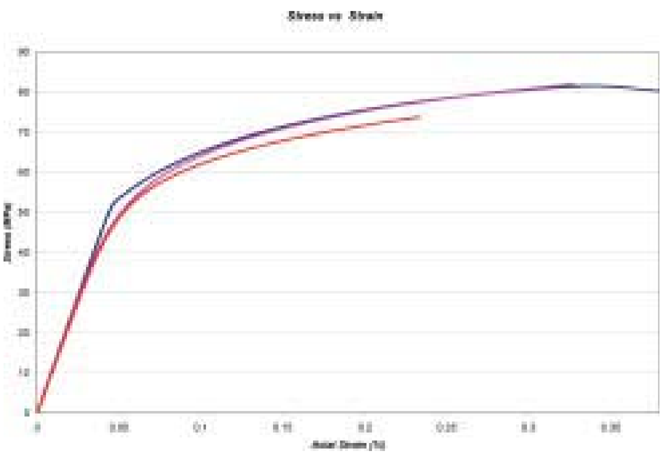

Figure 5. Axial tension stress-strain curves.

The strains to failure for transverse tension and shear were significantly lower than expected based on published literature for similar MMC materials. The data were checked to determine if the strain gages may have come loose during testing, but since the strain dropped off only as the load dropped off, there is no evidence to support this hypothesis. The lower strains are most likely driven by the fiber angle, which has a significant effect on strain. Filament winding of hoop fibers does not produce a purely 90° fiber orientation with respect to the axis of the cylinder. Deviation from the 90° theoretical is a result of the fiber band width and the need to traverse the length of the mandrel.

Table 3. Results from axial tension testing.

Sample Number	E (GPa)	q (MPa)	Strain @ Max Stress (%)
1	116	82	0.340
2	115	82	0.327
3	106	74	0.233
Average	112	79	0.300
Std. Dev.	6	5	0.058
Cv (%)	4.9	5.8	19.5

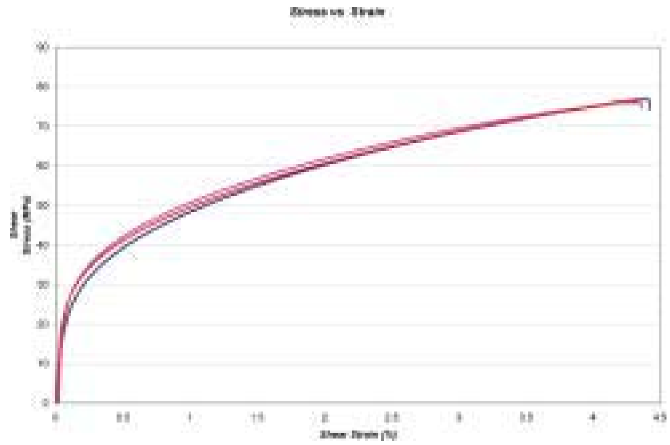

Figure 6. Shear stress-strain curves.

Table 4. Results from torsion testing.

Sample Number	G (GPa)	S (MPa)	Strain @ Max Stress (%)
1	31	80	4.396
2	54	78	4.329
3	28	79	4.361
Average	38	79	4.362
Std. Dev.	14	1	0.034
Cv (%)	36.8	1.3	0.8

Hydrostatic Burst Test Results

Hydrostatic burst testing of composite cylinders is a typical way to determine the as-wound longitudinal properties of the material. The test cylinder is sealed off at the ends and pressurized to failure. The burst pressure, which is the internal pressure at which the cylinder fails, is used to determine the delivered fiber strength as shown in Equation 1.

$$\text{Delivered Fiber Strength} = \frac{pr}{tVf} \qquad [1]$$

The delivered fiber strength is then compared to the theoretical fiber strength and is expressed as the translation efficiency. A high translation efficiency number means that the process is not damaging the fibers and that the matrix/fiber combination is working properly from a load transfer perspective.

The objective of this testing was to begin to understand the performance of filament wound MMC materials when hoop and helical plies are combined. These test data will be used to augment and improve preliminary modeling efforts. Table 5 shows a summary of the results for the tests performed on hoop-only cylinders and cylinders with a combination of hoops and helicals.

As indicated by the numerical results and evident from the post-test photographs in Figure 7, the additional helical plies in the 89/±45/89 laminate are not enough to drive the failure into the hoop fibers. However, with the addition of another helical layer, as is the case with the ±45/89/89/±45, a hoop fiber failure mode is achieved.

Conclusions

The results obtained in this study show that MMC filament wound cylinders behave in a similar manner as other composite pressure vessels, with the exception of the presence of significant non-linear effects in the transverse tensile response. While the translation efficiency is not as high as some polymer composite systems, it is essentially equivalent to what is typically observed for high modulus carbon fiber systems. Since the Nextel 610 fiber is a high modulus, low strain fiber, these results are within expectations. It is also encouraging to note that MMC pressure vessels follow the same design trends as other composite material systems. Additional development effort is needed to more fully understand the performance of MMC pressure vessels as a function of helical ply angle. A scale-up of the existing process will be needed before lower angle helical plies can be wound. Other areas of the technology that are currently being developed include the design and performance of integrally wound end domes and attachment methodologies.

Table 5. Summary of MMC cylinder hydroburst testing.

Lay-up	Test Type	Wall Thickness (mm)	Burst Pressure (MPa)	Delivered Fiber Strength (MPa)	Translation Efficiency (%)	Failure Mode
$[89]_4$	Uniaxial	1.27	19.4	1815	66	Hoop Fiber
$[89]_4$	Biaxial	1.30	5.4	483	18	Axial
89/±45/89	Biaxial	1.37	10.1	1068	39	Axial
±45/89/89/±45	Biaxial	1.73	19.1	1622	59	Hoop Fiber

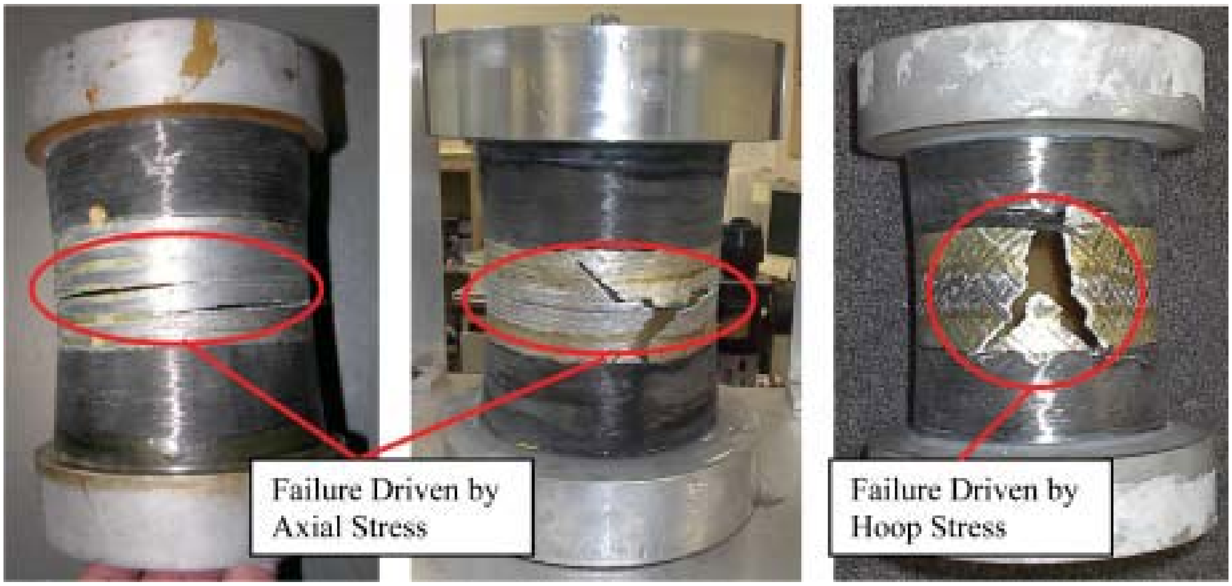

Figure 7. Biaxial hudroburst test failures: hoop-only (left), hoop-helical-hoop (middle), and helical-hoop-hoop-helical.

In conclusion, metal matrix composite materials hold great promise for improving performance of pressure vessels and metallic structures. Filament winding of MMCs will provide a way to produce components from these materials using a low-cost processing route that taps into the existing polymer composite processing equipment and knowledge base. In addition, producing cylinders in this manner will allow the efficient use of this material with minimal, if any, post-machining needed with the potential for using integral, wound-in end closures. Also, the finished part cost will be comparable to high performance polymer matrix composites.

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