METAL PREPREG TECHNOLOGY UPDATE

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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 areas of filament winding and tape production. The MMC filament winding process is now capable of winding hoop and helical plies. Hydroburst testing of recent cylinder specimens have demonstrated delivered fiber strength of 320 ksi, which represents a translation efficiency of 80%. This process is now ready to move to the next step of winding end domes and closures. The MetPreg tape manufacturing process has been extended into other materials combinations. Prepreg tape made from high-strength aluminum alloy matrices shows great promise for applications demanding high compression strength. Tape has also been manufactured with continuous carbon fibers in a magnesium matrix. This product is a potential beryllium replacement material and could also be used to manufacture lightweight mortar bipod leg tubes. This paper describes Touchstone's recent efforts to advance this unique technology.

KEY WORDS: Metal Matrix Composites/Structures, Filament Winding, Manufacturing/Fabrication/Processing

1. 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 would provide an economical means of utilizing the beneficial aspects of these materials.

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 paper describes Touchstone's current efforts to develop this technology, specifically in the areas of filament winding and selective reinforcement. Filament winding combines the MetPreg tape pultrusion process 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. Reinforcing metallic structures to improve strength and stiffness is another emerging market for MetPreg tape. Strategic placement of MetPreg tape into metals dramatically improves the properties with only minimal weight gain.

2. MATERIALS

2.1 Matrix Alloys The filament winding and tape processes have both focused on pure aluminum containing alumina fibers. In addition to pure aluminum, a wide range of aluminum alloys can be used for filament winding and selective reinforcement. Heat treatable alloys such as the 2*xxx*, 6*xxx*, and 7*xxx* series can be incorporated into metal prepregs. Generally, heat treatable alloys significantly strengthen the matrix, which substantially increases the shear strength but which can reduce tensile strength. The increased shear properties of the matrix also lead to a higher compressive strength. Proper selection of matrix material allows one to tailor the mechanical properties for a wide range of specific applications.

2.2 Fibers Aluminum oxide (α-Al_2O_3) fibers are used effectively as high-strength, high-modulus reinforcement in aluminum-based MMCs and have been used predominantly in the work completed thus far. Other fiber types, such as carbon or glass fibers, may be used depending on the strength and stiffness requirements of the finished component.

2. MMC FILAMENT WINDING

2.1 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**.

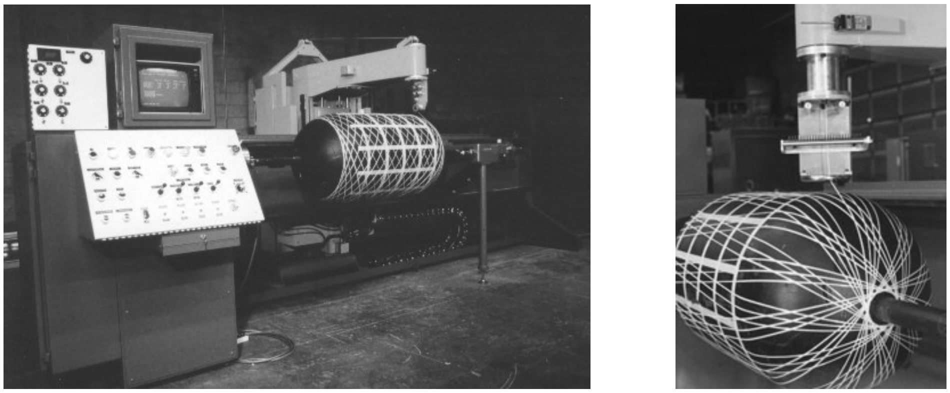


Figure 1. Composite Filament Winding

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 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.

2.3 MMC Cylinders Produced Filament winding of MMC cylinders can be accomplished in the same manner as described in the previous section. The resin, of course, must be replaced with aluminum, and the aluminum must be kept molten. This necessitates the use of materials for mandrels and other components that perform well at elevated temperatures in order to accommodate the higher temperatures of the process. The materials that give acceptable performance, however, such as graphite, would not be classified as exotic. Using this process, cylinders have been produced with inner diameters ranging from 5 to 10 cm with a length of up to 25 cm. **Figure 2** shows four of the cylinders that have been produced to date.

Figure 2. MMC Filament Wound Cylinders

Filament winding with MMC materials can be accomplished within the same design parameters as with organic composite materials. Hoop plies and helical layers can be achieved in order to meet the design requirements of the finished component. Helical ply angles of 45° and 68° have been demonstrated thus far. **Figure 3** shows a close-up view of a 45° helical layer.

Figure 3. MMC Filament Wound Helical Layer

Lower helical angles are possible and will be the focus of process and equipment upgrades to be completed in the near future.

2.4 Test Results Touchstone conducted process trials to determine the settings required to produce filament wound MMC tubes for hydrostatic burst (hydroburst) testing. Tow tension, band width, and pay-out mechanisms were evaluated during these initial trials. The best combination of these variables was chosen, and several test cylinders were fabricated. The cylinders were fully consolidated and upon metallographic inspection showed no evidence of voids or delaminations (**Figure 4**). These initial cylinders were tested at Touchstone to ensure that pressure containment could be achieved and to gain some understanding of how the cylinders would fail when internally pressurized.

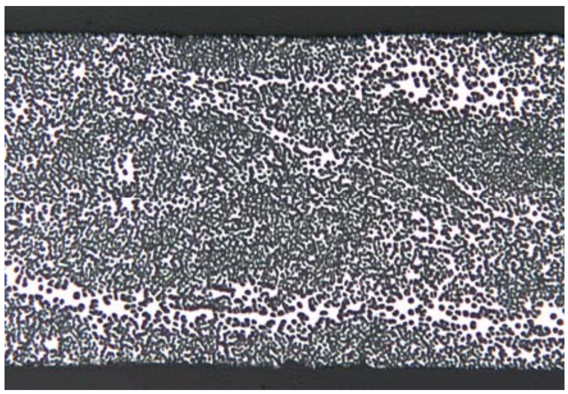
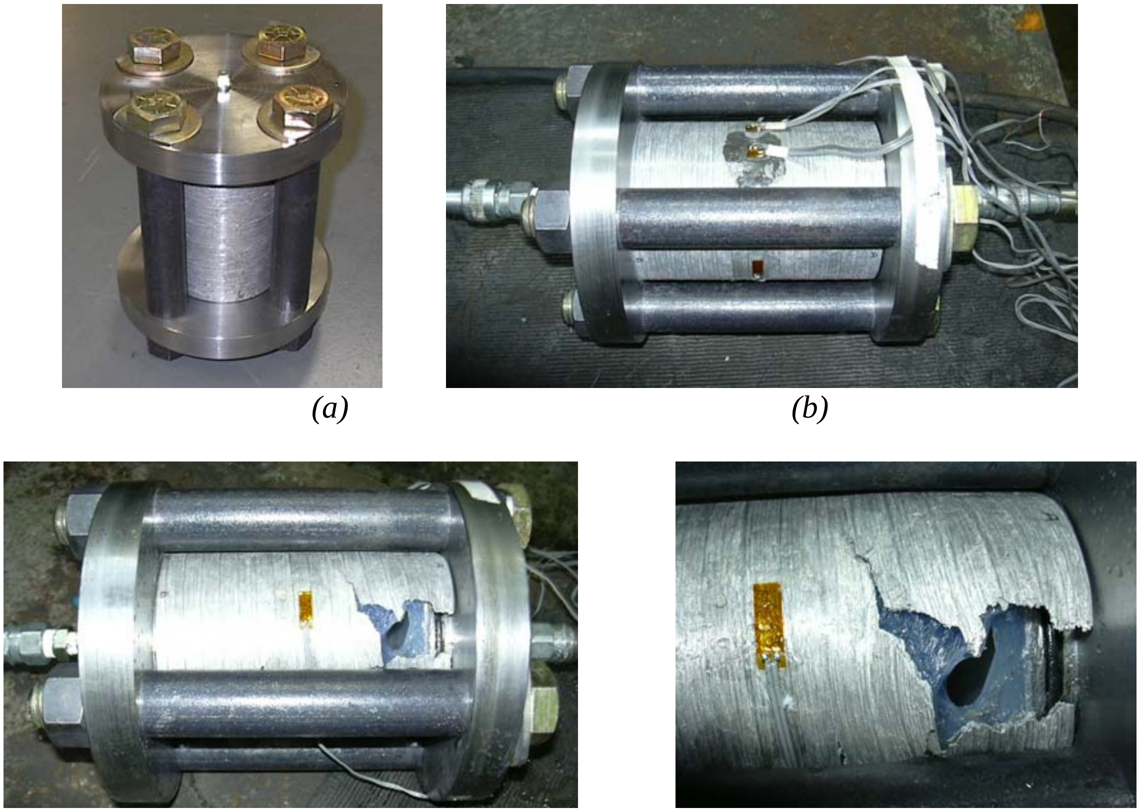


Figure 4. Metallographic Section of MMC Filament Wound Cylinder

The hydroburst test fixture was designed and fabricated by Touchstone. It consists of a flat plate milled to form a boss which functions as a plug with an O-ring to seal against the internal wall of the test cylinder. Two of these plates are secured by bolts and separated by spacers allowing the test specimen to "float" on the plate plugs. Due to the surface texture and roundness of the MMC cylinders as fabricated, a flexible internal liner was required to achieve proper sealing of the ends. This was accomplished with a combination of HTPB R45M rubber and Papi 20 curative compound. This is the same type of elastomeric liner typically used when high pressure testing of composite cylinders is performed. The results obtained from these initial trials were encouraging.

After completing the initial trials, Touchstone produced and shipped one filament wound MMC cylinder to Alliant Tech Systems (ATK) Tactical Systems Company (Rocket Center, WV) to be tested using its standard composite cylinder hydroburst testing protocol. The cylinder was composed of four hoop plies, had a diameter of approximately 102 mm (four inches) and a length of approximately 152 mm (six inches). The cylinder was manufactured with the same process settings as the trial cylinders. **Figure 6** shows the test cylinder in various stages of testing procedure.



(a) *(b)* *(c)* *(d)*

Figure 6. Hydroburst Test Set-up: (a) Cylinder in Test Fixture, (b) Cylinder After Attaching Strain Gages, (c) Cylinder After Bursting, and (d) Close-up of Failure Location

The test specimen burst at an internal pressure of 23 MPa (3375 psi). This correlates to a lamina strength of 636 MPa (92.3 ksi). The measured wall thickness was 1.85 mm (0.073 inches) and inner diameter was 101 mm (3.994 inches). The key performance parameter is the delivered fiber strength which is calculated as shown in **Equation 1**.

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

With a fiber volume of 35%, the delivered fiber strength is 1820 MPa (264 ksi). No leakage was observed before failure. Failure occurred on one end in a fairly localized manner. Measured hoop strain from the uniaxial strain gages averaged 0.40% with minimal deviation. Two bi-axial gages were installed and measured approximately 0.2% average in the hoop direction. This variation may be due to the much smaller gage length than the uniaxial gages. The accompanying axial gages measured 0.05% compressive, due to Poisson's effects. Assuming a longitudinal modulus of 186 GPa (27.0 Msi), the theoretical hoop strain at failure was 0.36%. The translation efficiency, which is a ratio of the delivered fiber strength with the 2758 MPa (400 ksi) theoretical fiber strength, is another measure of cylinder performance. The translation efficiency for this cylinder is 66%, which is respectable considering ATK's experience suggests high modulus graphite fibers in epoxy typically generate translation efficiencies of only 65%.

After this first round of testing was completed, a process modification was implemented that led to improved performance. Delamination between plies was observed within previously tested cylinders. The process was changed in order to reduce the chances of an oxide layer forming between plies during the winding operation. Cylinders produced after implementing the change to the process demonstrated increased delivered fiber strength to 2212 MPa (320, 856 psi) which represents a translation efficiency of 85%. **Table 1** summarizes the test results for the before and after conditions.

Table 1. Key Results of Hydroburst Testing

	Wall Thickness (mm)	Length (mm)	Inner Radius (mm)	Fiber Volume Fraction	Burst Pressure (MPa)	Delivered Lamina Strength (MPa)	Delivered Fiber Strength (MPa)
Before Change	1.85	152.4	50.72	0.35	23	636	1820
After Change	1.30	152.4	50.80	0.33	19	730	2212

3. SELECTIVE REINFORCEMENT

Last year Touchstone introduced the MetPreg metallic prepreg tape product line, which is manufactured on the company's multi-purpose MMC continuous infiltration machine. These metallic prepregs can be laid up by hand or with automated placement machinery. As such, they can be used for creating MMC laminates for high temperature applications. Another use of these tapes is to strategically place them onto or into metallic components as a means of providing additional strength or stiffness in specific areas. This concept is broadly referred to as "selective reinforcement" and can lead to reduced structural weight and increased structural performance. Selective reinforcement can also lead to reduced fabrication cost and can provide a means of designing for maintainability. This approach is a change in basic design philosophy that results in the development of a hybrid material form. Most new materials, or material forms, are established with little insight into the needs of the structural engineer or other down-stream participants. In the case of "selective reinforcement" the structural design approach defined the material form, which is the reverse of the typical flow path. Current material forms have shown, through analysis, that selective reinforcement could be a paradigm-changing design approach. MetPreg tape can be produced with various fiber and matrix materials such that the reinforcing material can be tailored to the specific application. For example, high strength aluminum alloy matrices work best for applications demanding high compression strength. Another version of MetPreg tape that is being developed incorporates high strength carbon fibers in a lightweight magnesium matrix.

3.1 Benefits of Selective Reinforcement **Figure 6** shows graphically the relationship between performance and cost as a function of percentage of reinforcement. Selective reinforcement entails looking at small amounts of reinforcement material applied to the base structure. Due to the higher cost of MMC materials, an increase in component cost will occur with the addition of reinforcement material and the subsequent attachment of the material to the base structure. Even at low reinforcement levels, however, the resulting performance benefits are huge. Once the amount of reinforcement exceeds a few percent of the total volume, the slope of the performance curve dramatically decreases while the slope of the cost curve increases. At a point where the structure is primarily comprised of a reinforced material, the slope of the cost curve could dramatically increase due to changes in the fabrication processes.

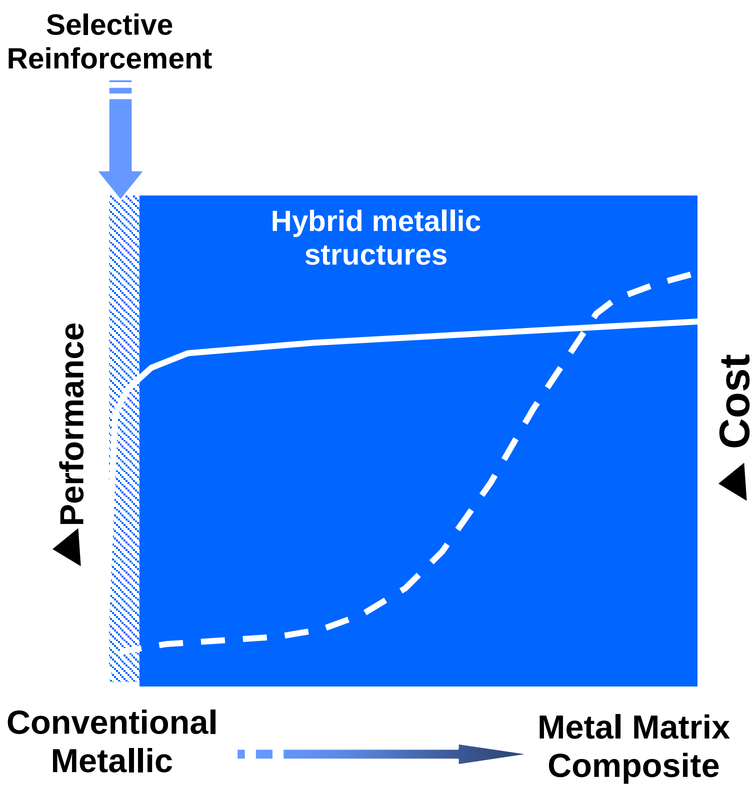


Figure 6. Performance and Cost Trade-offs for Selectively Reinforced Structures

3.2 Fatigue Crack Growth Embedding strips of MMC material into an aircraft wing or fuselage skin surface would clearly have an effect on local stiffness and strength. Recent testing performed at NASA Langley Research Center Vehicle Technology Directorate shows that this approach also dramatically improves fatigue crack growth resistance. The baseline specimen is an unreinforced 7075 aluminum alloy compact tension specimen. A selectively reinforced specimen, as shown in **Figure 7**, is also tested under the same condition. **Figure 8** shows the results of measurements taken by NASA. The crack length (a) of the unreinforced aluminum specimen grows nonlinearly with the number of fatigue cycles. This is typical trend data for aluminum. From the outset the selectively reinforced specimen produced a lower slope curve (smaller da/dN). When the crack reached the edge of the reinforcement, it could no longer be visually tracked. At the edge of the reinforcement, the reinforced specimen required 40% more fatigue cycles to grow the crack the same distance as the baseline specimen. The fatigue test of the reinforced specimen continued to 200,000 cycles, and the specimen was sectioned until the end of the crack was located. The reinforced specimen required 92% more cycles to reach this point than the baseline specimen. A second test has been conducted out to 500,000 cycles, and the data duplicates that which is depicted in **Figure 8**. The final crack length has been determined through sectioning the specimen. The difference in crack lengths for the 200,000 and the 500,000 cycle specimens is within the data scatter between specimens observed prior to the crack tip extending beneath the reinforcement. Therefore, it cannot be determined if crack arrest or just severe crack retardation occurred as the crack grew under the reinforced material. In either case, these data show a significant improvement in crack growth resistance. This demonstrates, at the coupon level, that utilizing selective reinforcement on the skin structure for improved panel stiffness also gives a dramatic increase in fatigue crack growth resistance.

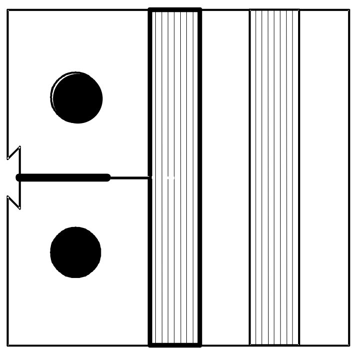


Figure 7. Compact Tension Specimen Used for Fatigue Crack Growth Test

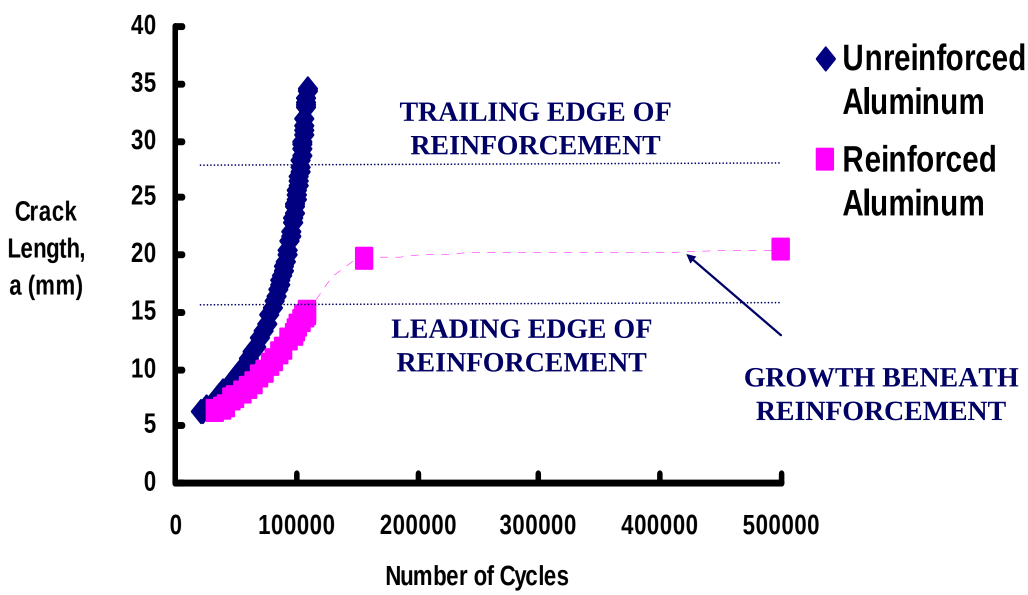


Figure 8. Fatigue Crack Growth Data

3.3 Open-Hole Compression Open-hole compression testing was also conducted by the Army Research Laboratory's Vehicle Technology Directorate. Testing was performed on square aluminum panels with 12.7 cm diameter cut-outs. The reinforced panels incorporated MetPreg tapes as selective reinforcement (**Figure 9**) to enhance buckling and post-buckling response.

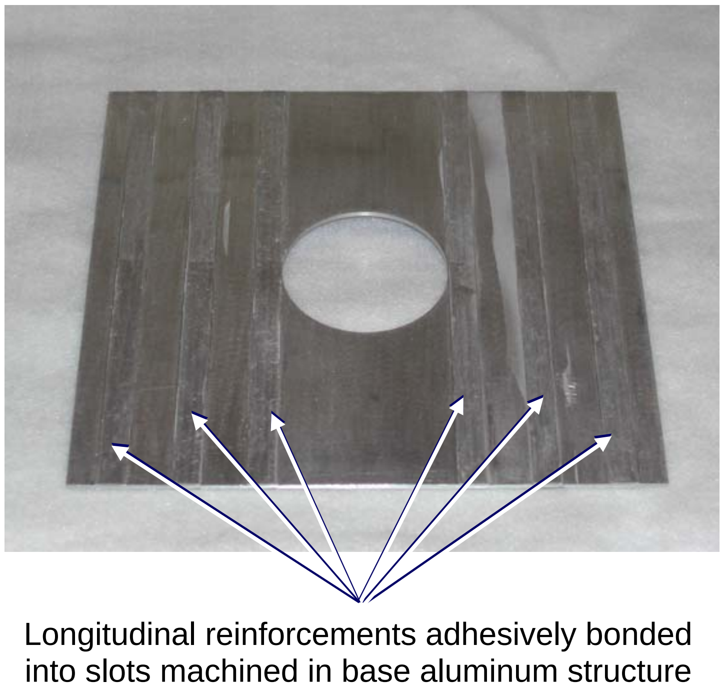


Figure 9. Open-Hole Compression Specimen

The selectively reinforced panels tested at ARL exhibited a 33 percent higher buckling load than the unreinforced panels. It should be noted that the addition of the reinforcement results in a small weight gain of approximately 2 to 5 percent depending on the reinforcement architecture; however, the specific buckling response, which includes the relative weight of the panels, exhibited a 23 to 68 percent increase relative to the unreinforced aluminum panels.

5. CONCLUSIONS

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. Through the strategic incorporation of reinforcing material, significant improvement in strength, stiffness, fatigue crack, and buckling performance of metallic structures can be achieved, providing a cost-effective way of taking advantage of the benefits offered by MMC materials. Current MetPreg tape production capacity can easily support these efforts.

6. ACKNOWLEDGEMENTS

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