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*Prepregs and  
Fabrics*

# MetPreg™

## Metallic Prepregs for the Composites Industry

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### Abstract

*Touchstone Research Laboratory Ltd. is developing metal matrix composite (MMC) technology that produces continuous fiber reinforced metallic prepregs analogous to polymer matrix composite (PMC) prepregs. The Touchstone metallic prepreg products, marketed under the name MetPreg™, combine beneficial attributes of light metals such as aluminum with those of high-strength, high-modulus reinforcement such as aluminum oxide continuous fiber. Metallic prepregs can be assembled into product forms by using manufacturing processes similar to those commonly used in PMC manufacturing. MetPreg constructions can be used under conditions normally outside the usage envelope of thermosetting and thermoplastic PMCs. These environments include elevated temperatures (greater than 400°C), cryogenic oxygen and hydrogen storage, severe cyclic temperatures, high vacuum, and high-pressure H<sub>2</sub> gas. Additionally, for many applications, mechanical performance rivals or exceeds that of premium carbon fiber reinforced composites. No curing processes are required. Since common equipment can be used for fabrication of PMC and MMC/MetPreg shapes, it is conceivable that a manufacturer can produce both types of products without major additional capital investment.*

*This paper describes Touchstone's advancements in metallic prepreg manufacturing and discusses evolving applications.*

### Introduction

#### **Background**

Metal matrix composites (MMCs) consist of a metal or metallic alloy matrix reinforced by fibers, 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 thermal 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. Touchstone's vision is to create a fiber reinforced metal industry 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.

## ***Metallic Prepregs Make Fiber Reinforced MMCs Producible and Affordable***

Touchstone has developed a manufacturing process for producing metallic prepreg tape comprising continuous reinforcing fibers in an aluminum matrix. Such prepreg tape contains nominally 50% fibers by volume, but fiber contents up to 60% by volume have been demonstrated. Tape thicknesses ranging from 0.15 to 0.50 mm are being produced with widths ranging from 10 to 40 mm. Other geometries outside of this range are also possible for the reinforcement levels cited above. Prepreg tape strips of 300 meters allow utilization of metallic prepregs in automated tape placement machines common to the polymer composite industry. This article focuses on recent accomplishments at Touchstone in the area of metallic prepregs.

## **Material Considerations**

### ***Comparison of Polymer and Metal Prepregs***

**Table 1** shows a comparison of processing differences and distinguishing properties of selected polymer and metal prepregs. Just as there are fundamental differences between metals and polymers, there are notable differences between PMC and MMC prepregs and resulting composites. As set apart in **Table 1**, polymer prepregs are more sensitive to environmental conditions, such as moisture and temperature, than are metallic prepregs. Expansion and contraction upon thermal cycling is much more likely to produce microcracks in polymer systems than in metals. Similarly, gas permeability through resin matrices causes design limitations for some polymer composite pressurized gas storage vessels. Conversely, aluminum is practically impermeable to most gasses, making composites of aluminum matrix prepregs highly useful for storage tank construction. With few exceptions for recently developed high-performance matrix resins, MMCs are capable of functioning at considerably higher temperatures than either PMCs or unreinforced aluminum. The tensile strength of some high strength carbon fibers exceeds the strength of continuous aluminum oxide fibers used in MetPreg aluminum prepregs; however, under shear stresses, MMCs significantly outperform PMCs. By placing a high stiffness fiber like aluminum oxide fibers in a high strength alloy such as AA6061, longitudinal compressive strengths of up to 4.5 GPa can be reached which is approximately a factor of three above that of PMC materials.

<b>Table 1 – Comparison of Behaviors and Properties of Polymer and Metal Prepregs</b>		
<b>Behavior/Property</b>	<b>Polymer Prepreg</b>	<b>Metal Prepreg</b>
Moisture absorption	Sensitive/swells	Not applicable
Storage environment	Refrigerated	Ambient
Upper use temperature	$\leq T_g$ of matrix	$\sim 0.6 T_{melt}$ of matrix
Matrix property optimization	Curing step required	Solidifies upon cooling
Tensile/compressive strength	Maximum parallel to fibers	Maximum parallel to fibers
Shear strength	Lower than metal prepregs	Controlled by alloy selection
Typical maximum shear strain	5%	1.6%
Tensile modulus of elasticity	160 GPa (Gr/Ep)	200GPa
Electrical behavior	Usually insulating	Conductive

## **Matrix Alloys for Metallic Prepregs**

In addition to pure aluminum, a wide range of aluminum alloys have often been used in MMC's. Heat treatable alloys such as the 2XXX, 6XXX and 7XXX series can be incorporated into metal prepregs. Generally, heat treatable alloys significantly strengthen the matrix, which substantially increases the shear strength, but can reduce tensile strength. The increased shear properties of the matrix also lead to a higher compressive strength. These important design variables for MetPreg tape allow for the tailoring of mechanical properties for a wide range of specific applications.

## **Fibers for Metallic Prepregs**

Aluminum oxide ( $\alpha$ -Al<sub>2</sub>O<sub>3</sub>) fibers are used effectively as high-strength, high-modulus reinforcement in aluminum matrix prepregs. Other classes of less costly fiber reinforcements having demonstrated utility in aluminum matrix prepregs include glass (E-, S-, and R-glass) and carbon. Glass fibers provide a route to significantly strengthen aluminum at low cost. Carbon fibers facilitate increases in specific stiffness and specific strength at a lower density of prepreg.

## **Typical Properties of Continuous Aluminum Oxide Fiber Reinforced Aluminum Prepregs**

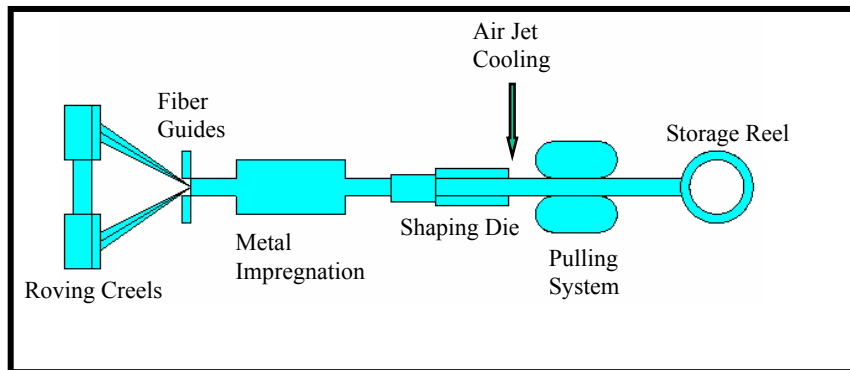
Table 2 gives typical properties of a MetPreg having a pure aluminum matrix with Nextel 610 continuous fiber.

<b>Table 2 – MetPreg Properties: Pure Aluminum Matrix with Al<sub>2</sub>O<sub>3</sub> Fibers</b>	
<b>Property</b>	<b>Value</b>
Fiber Volume Fraction	50 %
Thickness	0.50 mm
Width	9.50 mm
Density	3.30 g/cm <sup>3</sup>
Maximum Use Temperature	400 °C
0° Tensile Strength at RT	1500 MPa
0° Tensile Modulus at RT	215 GPa
0° Compressive Strength at RT	2070 MPa
Elongation	0.7 %
Thermal Expansion	7 $\mu$ m/m-K
Thermal Conductivity	115 W/m-K
Electrical Resistivity	50 n $\Omega$ -m

## **Processing Technology**

### **Metallic Prepreg Fabrication**

MetPreg unidirectional prepreg tape is manufactured on the Touchstone multi-purpose MMC continuous infiltration machine. **Figure 1** shows a schematic of the metallic prepreg manufacturing process. Fibers are passed into a molten bath of aluminum wherein wetting/infiltration of the fiber tows is accomplished. The infiltrated tow passes through a shaping die and is then cooled to give the desired metallic prepreg.



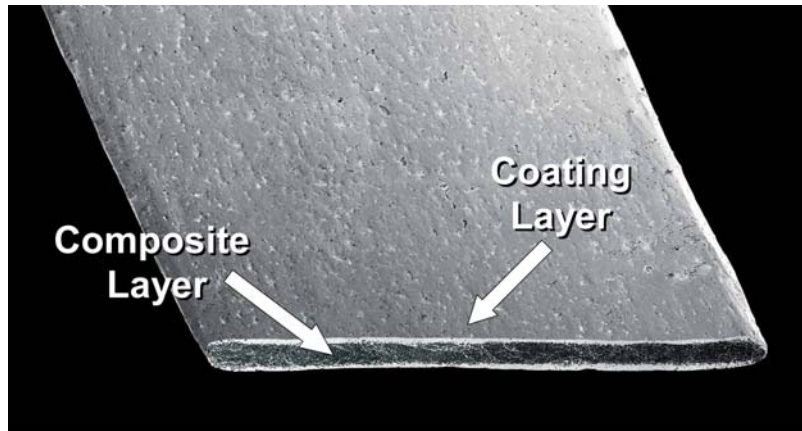
**Figure 1. Schematic of Metallic Prepreg Manufacturing Process**

This process is very similar to pultrusion processing used for producing continuous cross-section polymer composite components. As such, this setup is very flexible and adaptable for producing many standard seamless pultrusion profiles such: as rectangular tubes, channels, angles, and round tubes. **Figure 2** shows a variety of metallic prepreg shapes produced using this process. Following production, flat prepreg tape is wound onto a storage reel for subsequent part fabrication. Other shapes are cut to length and stacked.



**Figure 2. MetPreg Tapes and Pultruded Shapes**

After the tape making operation, various braze or solder coatings can be applied on the surfaces of the metallic prepreg which would be used in subsequent joining operations. **Figure 3** shows an end view of a piece of coated prepreg in which the fibers, matrix, and coating are visible.



*Figure 3. End View of Coated MetPreg Tape*

### **Lay-up and Consolidation of Metallic Prepregs to Yield Functional Components**

Metallic prepregs can be laid up by hand or with automated placement machinery. In either case, consolidation is achieved via welding, brazing, soldering, or adhesive bonding using an array of process techniques analogous to those found in the polymer composite industry. These include vacuum bagging, uniaxial hot pressing, hot isostatic pressing (HIPing), filament winding, and heated tape/fiber placement. Manufacturing processes utilized for MetPreg component production are shown in **Table 3** and also summarized below.

<b>Table 3 - Manufacturing Processes</b>	
■	Part Build-up <ul style="list-style-type: none"> <li>○ Hand Lay-Up</li> <li>○ Automated Tape/Fiber Placement</li> </ul>
■	Part Consolidation <ul style="list-style-type: none"> <li>○ Vacuum Bagging</li> <li>○ Hot Pressing</li> <li>○ HIPing</li> <li>○ Adhesive Bonding, Brazing, Soldering and Welding</li> </ul>

#### **Hand Lay-Up**

Metallic prepreg tapes can be made into multi-directional, multi-ply parts by manually laying the tapes into a fixture in the desired orientation as shown in **Figure 4**. Thin sheets of filler metal are laid into the fixture between the plies, or brazed coated tapes can be used. The laminate can then be consolidated in a vacuum furnace or placed in a metal container, such as a welded steel bag, that is evacuated and heated in an air furnace or a HIP.





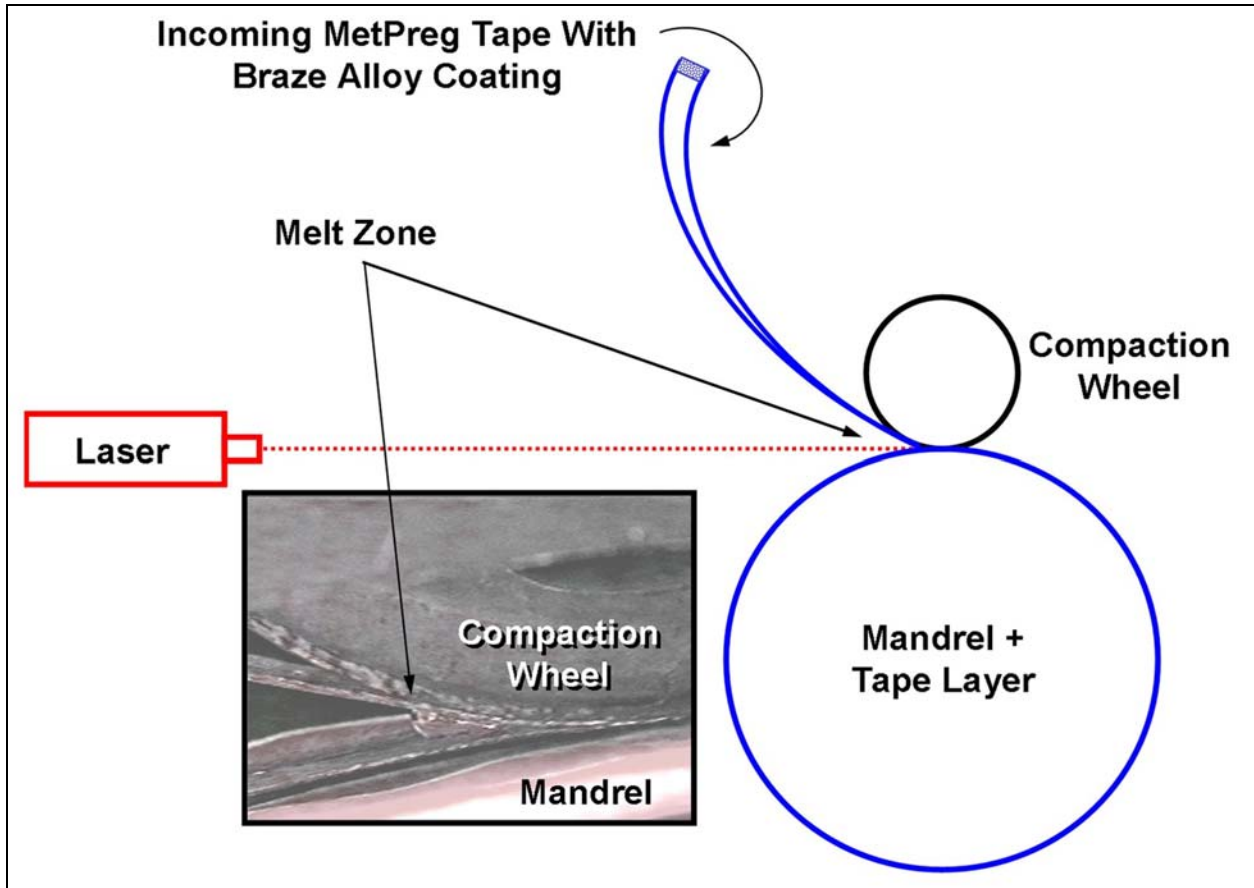
*Figure 4. Hand Lay-up of MetPreg Tape*

### **Uniaxial Hot Pressing**

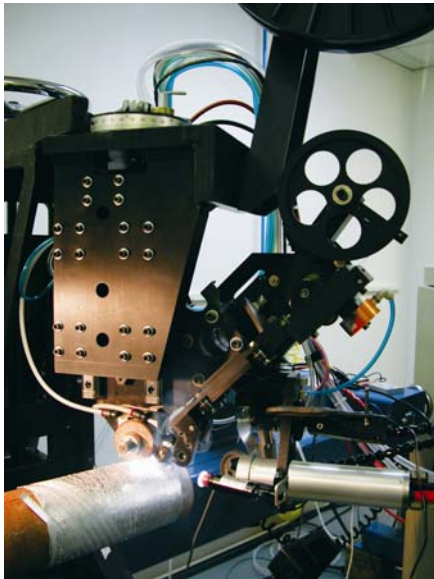
Uniaxial hot pressing can also be used to produce solid structures. An advantage of uniaxial hot pressing is that the bond layer is usually thinner, increasing the overall percentage of fibers in the final part. In hot pressing, uniaxial pressure is applied to flat or curved MMC laminated structures using a hydraulic, mechanical or pneumatic press.

### **Tape Placement**

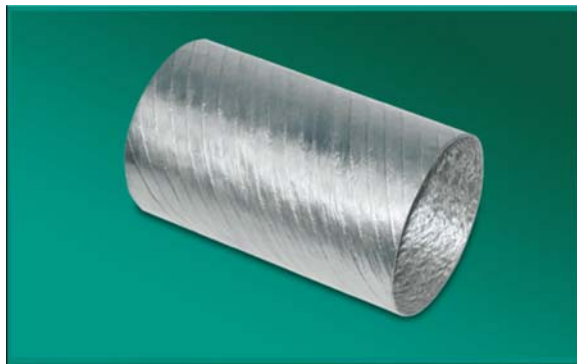
Touchstone has developed a device based upon traditional PMC tape placement processing but modified such that it uses a laser to continuously consolidate metallic prepregs. At the heart of this concept is the continuous or “braze-on-the-fly” technique that is utilized for consolidating the MetPreg plies. The prepreg is fed into the heating zone through rotation of the mandrel. As the coating layer is locally heated to its melting point and simultaneously pressed against the previously laid layer, a metallurgical bond is formed between the top and bottom prepreg layers. This is shown schematically in **Figure 5a**. Prototype equipment for accomplishing this process at Touchstone is shown in **Figure 5b** and a completed MetPreg cylinder is shown in **Figure 5c**. **Figure 5d** shows a metallographical cross-section of a multi-ply MetPreg laminate produced on the tape placement machine.



*Figure 5a. Schematic of Continuous Tape Placement Process*

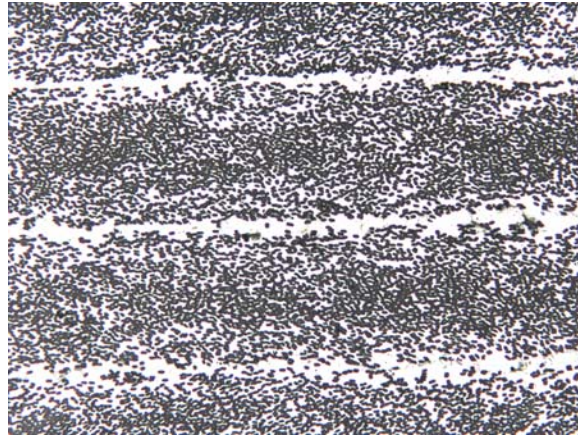


*Figure 5b. Tape Placement Machine*



*Figure 5c. Tape Placed MetPreg Cylinder*





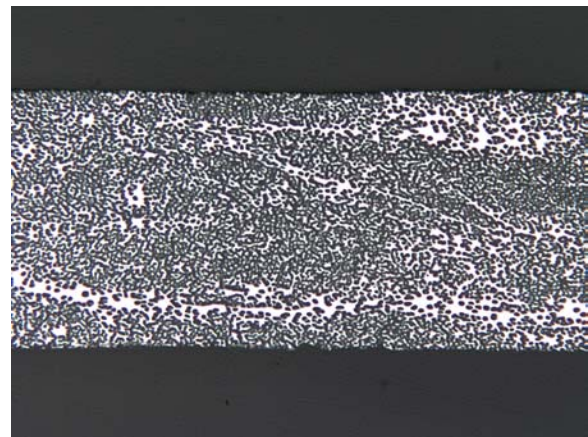
*Figure 5d. Microstructure of MetPreg Tape Placed Cylinder*

### **Filament Winding**

Another consolidation device developed by Touchstone Research Laboratory is the MetPreg filament winder. Just as with traditional filament winding, the MetPreg winder lays down wetted fibers onto a mandrel. In the case of the MetPreg filament winder, the tows are consolidated while the matrix is still molten. This yields a part with a fiber volume as high as 60%. A completed filament wound MetPreg cylinder is shown in **Figure 6a** and a metallographical cross-section of a multi-ply MetPreg laminate produced on the filament winding machine is shown in **Figure 6b**.



*Figure 6a. Filament Wound MetPreg Part*



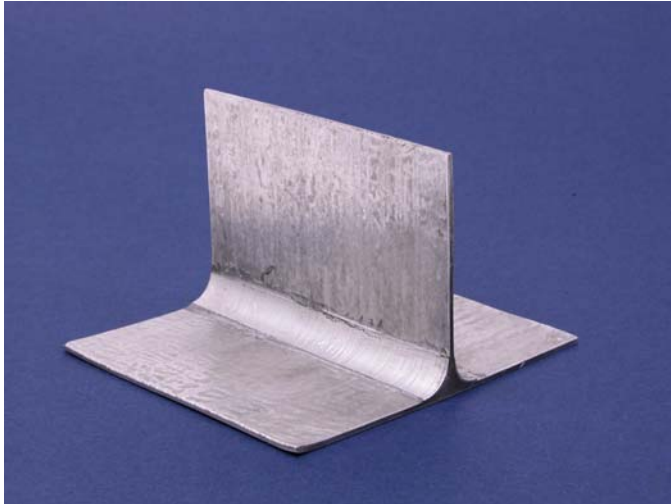
*Figure 6b. Microstructure of MetPreg Filament Wound Cylinder*

### **Attachment and Repairs**

MetPreg structures can be assembled with adhesives, solders, brazes as well as spot welding and ultrasonic welding. An advantage of metallic attachments is their inherently high bond strength – often many times the strength of adhesives. Adhesives have the advantage of simplicity.

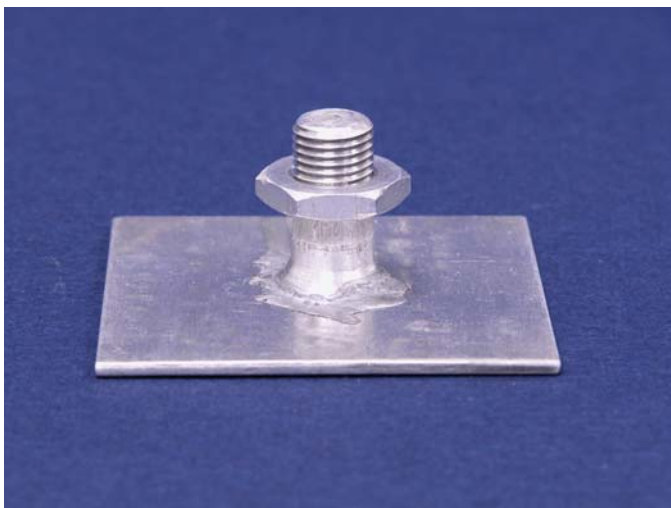
Joints between MetPreg panels are likely manufactured by soldering or brazing. Machined fillet inserts may also be used as in **Figure 7**.

Because of the high strength and stiffness of the aluminum matrix, metallic prepregs may, in many designs, hold the promise of lighter weight joints than PMC's.



*Figure 7. Two 0/90/90/0 MetPreg panels joined via soldering.*

Although the repair technology is far from developed, it is expected that MetPreg repairs will be made via soldering, brazing or welding and can be accomplished in minutes with tools as simple as oxy-acetylene torches.



*Figure 8. An attachment soldered to a 0/90/90/0 panel*

## Applications

### ***Pressure Vessels/Storage Tanks/Cryogenic Ducts***

One of the main goals of NASA is to develop routine, low-cost access to space. To achieve this goal, NASA is studying a variety of Reusable Launch Vehicle (RLV) platforms. Cryogenic tank development is critical for an RLV because the tanks may comprise as much as 70 to 80 % of the volume of the vehicle. Lightweight aluminum alloys have played an important role in the design and construction of launch vehicle fuel tanks and pressure vessels. Testing conducted at the NASA White Sands Test Facility on MetPreg materials demonstrated that there are significant advantages due to compatibility with liquid oxygen (LOX) and liquid hydrogen (LH<sub>2</sub>). Aluminum alloys are advantageous due to their compatibility with LOX and LH<sub>2</sub>. They also have very low permeability and, therefore, low loss of stored gases. However, emphasis on performance enhancements has led to the investigation of newer materials systems.

While there are several advantages to using a PMC pressure vessel rather than the traditional monolithic metal shell, there are also drawbacks that make aluminum based materials a better choice. The primary benefit of using a PMC containment vessel, for example, is weight savings which can improve the overall performance of the vehicle and increase fuel capacity. But, PMCs require metallic liners to avoid gas leakage through the composite shell. In addition, external shielding and other protections are needed because the vessels are fragile and can be easily damaged by being dropped, handled roughly, or by impacts of dropped tools or micro-meteorites. Another significant drawback is that most PMCs experience microcracking when cycled from cryogenic to elevated temperature. This typically leads to leakage of the propellant and failure of the tank.

In contrast, aluminum based materials do not exhibit microcracking, do not need to be cured after assembly, and their strength improves at cryogenic temperatures. They are, therefore, a better choice for this application. Touchstone's MetPreg technology represents an opportunity to manufacture large metal matrix composite (MMC) tanks and other components through the use of production processes that are analogous to PMC processes, while maintaining the beneficial MMC materials properties. Likewise, a major goal for establishing a hydrogen energy economy is to gain consumer acceptance for fuel cell-powered vehicles in the transportation sector. Hydrogen storage is a critical path technology that will facilitate the commercialization of these vehicles and the acceptance of this form of energy into our daily living habits. Lightweight materials that are compatible with compressed hydrogen and do not pose "leak-through" issues are highly desirable. Since the MetPreg technology is based on aluminum as the principle matrix material, it is a good candidate for providing lightweight storage tanks for off- and on-board compressed and liquefied hydrogen storage.

### ***Rocket Motor Cases***

Innovative rocket motor case materials and manufacturing processes are required to drive improvements in performance and price of today's rocket motors. Metals, particularly high strength steels, have played an important role in the design and construction of both strategic and tactical missiles. For example, the steel case used for air-to-air missiles is advantageous due to its ability to provide sufficient stiffness/natural frequency and to withstand aeroheating, without additional material thickness beyond that required to accommodate motor pressure. Metal cases also easily accommodate hooks/attachments used in captive-carry applications and are relatively inexpensive. However, currently evolving missile designs are moving towards higher pressures, higher and longer duration aeroheat temperatures, and increased maneuverability. Higher motor operating pressures and increased missile stiffness will require

materials and manufacturing processes exhibiting higher specific strength and stiffness than steels can provide.

PMC parts for this application typically use expensive resins and time-consuming fabrication and resin cure processes, sometimes including the use of large autoclaves. Even then, the maximum use temperature is only 260°C, and most PMCs must be combined with hefty heat shields that diminish the weight saving. Heat shields also lead to a reduction in propellant volume since motor case designs are typically constrained by outer diameter. In some applications, the loss of available propellant volume is also exacerbated by the thicknesses of PMC required to make up for the low matrix strength that is typical of most epoxies. Touchstone's MetPreg technology has the potential of eliminating the trade-off between low weight and internal volume. It has nearly the equivalent strength of steel with a 30% lower density, and the higher temperature capability translates into more internal volume due to the elimination of additional insulation.

### ***Artillery Shells and Mortar/Gun Tubes***

The Army has significant need for lightweight materials to meet the goals of the Objective Force, the fully transformed Army, in its roles as a joint force provider, joint force sustainer, joint force integrator and world's dominant full spectrum land force beyond 2010. Lightweight ordnance launcher applications are one area of great importance. These systems must be responsive, deployable, agile, versatile, lethal, survivable, and sustainable. In one scenario, using MetPreg as a strong, lightweight, high-temperature mortar tube material would lead to improved efficiency and greater range. Meanwhile, reducing the weight of current artillery shell systems can improve tactical mobility and increase payload on cargo-carrying systems. For example, the 155-mm diameter projectile (Excalibur) has a steel body, which represents 65% of the total projectile weight. A MetPreg shell can take advantage of the higher matrix strength and reduce the shell thickness while maintaining the benefits of reduced weight.

### ***Lightweight Structures for Transportation***

The weight savings offered by this technology would also produce benefits for the next generation of military and commercial transportation. One example is a lightweight, yet strong airframe for unmanned combat air vehicles, or UCAVs, the advanced version of the pilotless spy planes that have been used in recent conflicts. The battlefield of the future will also rely on other unmanned aerial vehicles to patrol the skies and survey enemy positions to help fill out a "common battlefield picture". Another example is lightweight components for use in armored vehicles and tactical trucks for tomorrow's Army. Future armored vehicles will weigh less than 20 tons and fit on a C-130 cargo plane, characteristics that will help the Army reach its new goal of being able to ship a full brigade anywhere in the world within 96 hours. Likewise, the 21<sup>st</sup> Century Truck program is aimed at developing lightweight, corrosion-resistant tactical trucks for military use. Commercial aircraft and ground transportation vehicles will also take advantage of the weight savings offered by the technology.

### ***Selective Reinforcement of Metallic Structures for Aircraft***

Since the Wright brothers' first flight of a heavier-than-air craft under its own power source, designers have searched for ways to improve both the efficiency and performance of aircraft. Aircraft technology has improved significantly during the first 100 years of powered flight. However, the next century will require even more significant technical advances.

One key research area related to advanced structural technologies is the study of controlling aircraft aeroelastic response to prevent the onset of flutter, buffet, and other undesirable aeroelastic phenomena by utilizing tailored structures that exhibit coupled deformations. Demonstrating bending-twist coupling

represents an important capability for future aircraft structures and has been one of the “holy grail” challenges for PMC materials. MetPreg may provide a unique solution to this problem that would provide the aircraft community with a low-cost, structural tailoring capability using predominantly conventional metallic materials that was the exclusive domain of PMCs. MetPreg tape can be used for selectively reinforcing aluminum structures, such as aircraft skins. This process represents an affordable way to selectively reinforce metallic structures using continuous fiber MMC materials that more closely match the base material. This approach allows the designer the freedom to place, at the given point, exactly the amount and orientation of fibers required by the load state at that point, thus achieving an optimal design.

### ***Flywheels***

Flywheels are ideal energy storage devices, with the capability of converting their store of kinetic energy to electric energy while requiring no chemicals and producing virtually no pollutants. Filament wound PMCs, specifically graphite-fiber/epoxy matrix composites, are a potential solution for this application because their high specific strength in the longitudinal direction gives them the ability to withstand large hoop stresses. However, polymer composites have inherently low matrix strengths. Consequently, high rotation speeds produce significant radial stresses within the matrix that lead to failure of the part before the hoop stress maximum is reached.

Flywheel rotors made from materials that have high specific strength in both the longitudinal and transverse directions and that maintain these properties at higher temperatures will enable the design of smaller flywheel systems with equivalent or greater total energy storage capacity. In addition, materials that do not out-gas in vacuum would reduce the failure modes associated with aerodynamic heating and potential problems with contamination within the confines of space vehicles. Touchstone’s MetPreg material system offers all of these desired properties. MetPreg flywheels would be smaller and lighter with significant performance improvements in total energy and specific energy.

### ***Sporting Goods***

Bicycle frames, tennis rackets, and golf club shafts may also benefit from the unique properties of MMCs. Benefits over steel and aluminum are easily realized through weight savings and improved stiffness. The benefits compared to PMCs may be more subjective, such as the effects of a more ductile matrix and the elimination of the “boardy” feeling associated with brittle-matrix materials.

## **Conclusions**

Metallic prepregs represent an opportunity for designing and manufacturing high-performance, cost-effective reinforced metal structures. They provide a significant increase in specific strength and stiffness over monolithic metals and overcome the current obstacles encountered when polymer composite materials are chosen for cryogenic or high temperature gas storage applications. Current pricing of aluminum matrix prepregs is comparable with high performance carbon fiber reinforced PMCs. Touchstone’s manufacturing process is also capable of producing metallic prepregs containing lower cost reinforcement fibers for less demanding applications. Since the prepreg tape can be utilized on existing PMC manufacturing equipment with only slight modifications, the cost of producing MMC components will be comparable to PMC part costs. Overall cost savings for MMC parts may be realized if touch labor and equipment costs associated with post-curing of PMC parts are taken into consideration. Metallic prepregs are an enabling technology that with continued development and market exposure will lead to revolutionary change in the composites industry.

## Acknowledgements

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