

## HIGH QUALITY CARBON FIBER EPOXY PREPREGS FOR A WIDE RANGE OF REINFORCEMENT ARCHITECTURES

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### ABSTRACT

Broad adoption of carbon fiber epoxy prepreg materials in the automotive industry requires carefully engineered fabric architectures so that fiber reinforcements are aligned to part loading paths, thus utilizing the carbon fiber most efficiently. However, maintaining high infusion into fabric reinforcements with a broad range of reinforcement architectures and areal weights requires a flexible resin system and detailed processing knowledge. Here, we report development of prepreg materials with a range of reinforcement architectures, spanning fiber areal weights from 186 gsm to 733 gsm, all based upon the hot melt VORAFUSE™ prepreg resin system. We observe low void, high quality molded parts under identical isothermal molding conditions. Finally, we relate prepreg architecture to performance of molded composite parts.

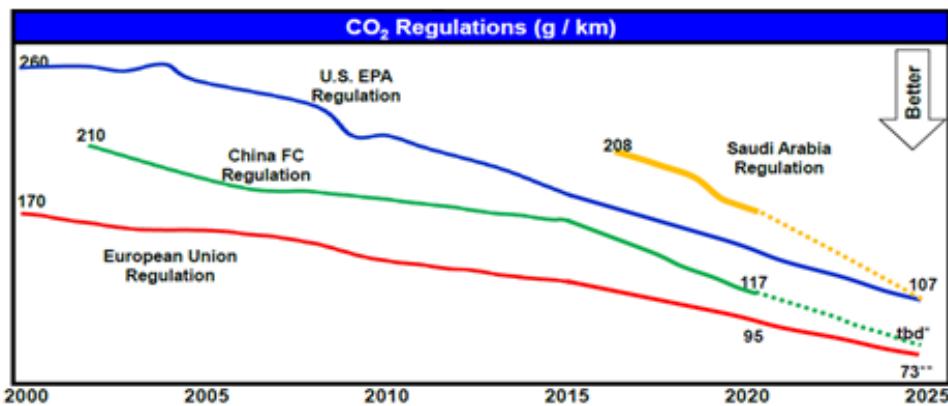
### INTRODUCTION

Meeting the global requirements for reduced CO<sub>2</sub> emission and increased vehicle fuel economy requires new technology development within the transportation industry. The impact of these pressures is evident in the passenger car market where increased regulation of exhaust emissions and fleet fuel economy have led to the need for advanced power-train engineering to meet current and future regulations. Results of this work have led to clean diesel technology, hybridization and electrification. However, even as powertrains evolve, it has become apparent that these changes alone may be insufficient to meet future performance requirements. While automotive manufacturers have made gains in fuel efficiency and reduced vehicle greenhouse gas emissions, meeting 2025 regulatory mandated fleet average fuel economies requires a step change in vehicle technology (Figure 1)<sup>1</sup>. This gap is creating a strong business case for mass reduction through use of lightweight structural materials, such as carbon fiber reinforced epoxy composites. Vehicle lightweighting is a particularly important approach because reducing primary vehicle weight can often enable secondary mass reductions and this could lead to mass decompounding<sup>2</sup>. A notable recent example of mass decompounding is the 2015 Ford F150, which achieved a 700 lb. vehicle weight reduction through increased use of advanced high strength steel, aluminum, and magnesium materials, in turn enabling use of more efficient powertrain technologies<sup>3</sup>.

Carbon fiber composites offer a considerable weight savings over steel, and every 10% reduction in vehicle weight can result in a 6%-8% fuel-economy improvement<sup>4</sup>. Dow Automotive Systems, partnering with the Ford Motor Company, has developed and is implementing carbon fiber composite materials for mass-produced automobile parts. The carbon fiber used in this joint effort is provided by DowAksa, a joint venture between The Dow Chemical Company and Aksa Akrilik Kimya Sanayii A.S. (Yalova, Turkey).

Present day carbon fiber composites represent a class of materials that have not been used in high volume production. As a result, component design, engineering, materials and manufacturing processes for the economical, high volume production of vehicle parts is not well understood. Therefore, Dow Automotive has focused on resolving these technical issues. The emphasis has been on delivering materials and

processes that promote rapid fabrication and assembly methods for light weight automotive composites that support production volumes in excess of 100k/year. Specific areas of technical development include carbon fiber preangs based on novel formulated epoxy systems and aligned fiber for compression molding of structural composites.



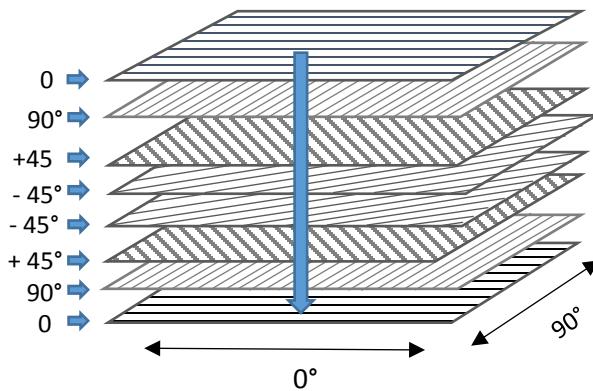
**Figure 1: Mandated change in vehicle CO<sub>2</sub> emissions measured during the New European Drive Cycle (NEDC) in grams of CO<sub>2</sub> per kilometer of travel as a function of time.**

### COMPOSITES FOR HIGH VOLUME MANUFACTURING

Manufacture of a composite structure starts with the incorporation of resin into the fiber to form a lamina or a ply. The fibers can be of two types, continuous or discontinuous (short) fiber. If continuous or long fibers are used, they can be 1) in a unidirectional orientation where all fibers are arranged in one direction; 2) in a bi-directional orientation, where fibers are arranged in two directions, usually normal to each other; or 3) multi-directional orientation. The bi-directional and multi-directional fabrics are most commonly produced by a weaving or braiding process.

A fiber is the primary load carrying element of the composite material. The composite material is only strong and stiff in the direction of the fibers. For a lamina consisting of unidirectional fibers, the composite has the highest strength and modulus in the longitudinal direction. However, the strength is very low in the transverse direction. Such materials are said to be anisotropic, since their mechanical and/or physical properties are direction dependent and vary relative to the inherent axes of the material. Materials such as glass and metal, on the other hand, are usually isotropic in nature. An isotropic material has uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing. Components made from fiber-reinforced composites can be designed so that the fiber orientation produces optimum mechanical properties, but they cannot fully replicate the true isotropic nature of metals.

Composite parts rarely utilize a single lamina because this unit is typically very thin. A thicker part and more balanced properties can be achieved by stacking several plies together and varying the orientation of each ply in the ply sequence. Such a stack is called a laminate (Figure 2). Since the strength and stiffness of a composite is determined by the orientation of the plies to the applied load, proper selection of ply orientation is necessary to provide a structurally efficient design. For example, a part might need plies in the 0° direction to react to axial loads, ±45° plies to provide reinforcement against shear loads, and 90° plies to react to side loads.



**Figure 2: Quasi-isotropic lay up of prepreg plies to form a laminate**

The advantage of unidirectional fiber is it allows for the customization of the fiber direction to the load direction. The ability to customize fiber direction enables the usage of only as much fiber as needed; rather than wasting material, costs, strength, and weight in directions where there is little to no load. However, the formability of unidirectional fabrics can be poor. Woven and braided fabrics provide superior handling, drapability and more balanced laminate properties.

A comparison of some of the most commonly used carbon fiber fabric types is shown in Table 1. Woven fabrics are made by interlacing warp ( $0^\circ$ ) fibers and weft ( $90^\circ$ ) fibers in a regular pattern. However, the tensile strength of woven fabrics is compromised to some degree because fibers are crimped as they pass over and under one another during the weaving process. Under tensile loading, these fibers tend to straighten, causing stress within the matrix system<sup>5</sup>. Braided fabrics are continuously woven on the bias and have at least one axial fiber that is not crimped in the weaving process. This architecture offers greater toughness and strength-to-weight than woven fabrics. It also has excellent formability, which makes it well-suited for production of preforms.

**Table 1: Comparison of selected fabric types<sup>6</sup>**

Fabric Type	Fabric Schematic	Possible Fiber Disposition	Advantages / Disadvantages
Unidirectional (UD)			High mechanical performance in fiber direction Poor performance in transverse direction Poor formability (fabric splits along fiber)
Weave (Twill)		2x1 2x2 3x1 3x3	Good formability Excellent durability high areal weights achievable
Non-crimp Fabric (NCF)		Unidirectional Biaxial Triaxial Quadraxial	More economical (stitching vs. weaving) High mechanical strength and stiffness Very high areal weights achievable Difficult to form due to stitching
Braids		Biaxial Triaxial Sleeves	Excellent formability, non-uniform contours Exceptional toughness High areal weights achievable

Non-crimp fabrics (NCFs) are nonwoven fabrics made with unidirectional fiber layers stacked in different orientations and held together by through-the-thickness stitching, knitting or a chemical binder. In NCFs, the fiber crimp associated with woven fabrics is avoided because the fibers lie on top of each other, rather than crossing over and under. This makes better use of the inherent strength of the fibers. NCFs are attractive because they are relatively cheap. However, these fabrics are more difficult to form due to the stitching.

Based on the target application and strength requirements, the appropriate fiber architecture can be selected to make the desired composite part. The selected fiber is then impregnated with a matrix resin to form a prepreg which can be stored. To achieve the desired three dimensional (3D) cured composite part from two dimensional (2D) carbon fiber prepreg, the following steps are required:

- Cutting the prepreg to required size via automated XY cutting table or die cutting
- Joining of multiple prepreg ply's using heat and pressure to achieve desired thickness
- Shaping (i.e. "preforming") of the prepreg stack into the 3D geometry of a part and integrated trimming of excess prepreg
- Isothermal compression molding of the preform

Prepreg materials suitable for high volume composite manufacturing must satisfy a number of requirements. The prepreg should have a long shelf life at ambient temperature. It should exhibit low tack. Having low tack would allow prepreg plies to be cut, picked up, stacked and placed on tables or molds without sticking to the grips, tables or other adjacent materials. Low tackiness also prevents sticking of prepreg plies to each other which can be useful in adjusting the orientation of the prepreg plies during automated layup. Another requirement for the prepreg is formability. Once the prepreg is thermoformed, it should hold its shape for at least 2 weeks at ambient temperature. In addition to all the above, a critical requirement for high volume manufacturing is a short molding cycle time. In order to achieve a cycle time of 3 minutes per part, the matrix resin should cure rapidly in 2 minutes at molding temperature. Finally, the manufactured part should possess the desired mechanical properties. Epoxy resin systems can be tailored to undergo extremely fast cure, possess very high strength, dimensional stability, as well as high temperature and moisture resistance. Dow Automotive Systems has developed a novel epoxy-based rapid cure, aligned fiber material, VORAFUSE™ P6300 prepreg that satisfies all the above mentioned requirements. This prepreg product is based on a hotmelt epoxy resin formulation.

A broad adoption of carbon fiber epoxy prepreg materials in the automotive industry requires carefully engineered fabric architectures so that fiber reinforcements are aligned to part loading paths, thus utilizing the carbon fiber most efficiently. The VORAFUSE™ P6300 hotmelt epoxy resin system is well suited for infusion into a broad range of reinforcement architectures and areal weights. The low uncured glass transition temperature and very low viscosity of the resin system at infusion temperatures enables rapid impregnation into the fabric reinforcement while minimizing void spaces within the prepreg. In this paper we share the results of our efforts to develop prepreg materials with a range of reinforcement architectures, spanning fiber areal weights from 186 gsm to 733 gsm, using various fabric architectures, all based upon this hot melt prepreg resin system.

## FABRICATION AND EXPERIMENTAL TECHNIQUES

The prepregging process was as follows: the prepared resin mixture was first filmed to an appropriate thickness on one side of a release paper. Since the resin system becomes tack free once it cools down to room temperature, the resin film can be rolled up and stored until future use. To fabricate the prepreg, the selected fiber architecture was sandwiched between two layers of the filmed resin and passed through a prepreg line containing heated tables that melt the epoxy resin, and compaction rollers that press the

melted epoxy resin into opposite surfaces of the fabric. The prepreg was rolled up after it had passed beyond the heated rollers and the chiller plates. Rolls were stored at ambient temperature.

Four carbon fiber architectures were investigated. The details of the fabrics are shown in Table 2 below. The unidirectional (UD), 2X2 twill and non-crimped fabric (NCF) were obtained from DowAksa. The two-dimensional braid fabric was obtained from A&P Technology. The fiber architecture of the NCF and braid was  $0^\circ/+60^\circ/-60^\circ$ . The  $0^\circ$  axial fibers were 24k flattened tows while the  $\pm 60^\circ$  bias fibers were 12k flattened tows. (The terms 24k and 12k refer to the number of fibers in the fiber tow.)

**Table 2: Carbon fiber fabric specifications**

Fabric	Fiber Areal Weight	Fabric Architecture	Tow Specification	Fabric converter
UD	186 gsm	$[0^\circ]$	A42-D012 24k	DowAksa
2X2 Twill	380 gsm	$[0^\circ, 90^\circ]$	A42-D012 12k	DowAksa
NCF	590 gsm	$[0^\circ, +60^\circ, -60^\circ] [0^\circ, -60^\circ, +60^\circ]$	Axial:A42-D012 24k Bias:A42-D012 12k	DowAksa
Braid	733 gsm	$[0^\circ, +60^\circ, -60^\circ]$	Axial:A42-D012 24k Bias:A42-D012 12k	A&P

Flat panel composite laminates were molded from 12 x 12-inch squares of prepreg. The molding conditions were as follows: Platen temperature of 150 °C; 15 seconds to close tool; 15 seconds at 350-500 psi; 2.5 seconds ramp to 2500 psi with 150-270 seconds hold. The target thickness for molded plaques was 2.2-2.4 mm, with the following layup of plies for each carbon fiber type:

- 12 plies of 186 gsm UD:  $[0^\circ]_{12}$
- 6 plies of 380 gsm twill
- 4 plies of 590 gsm triaxial NCF: balanced lay up;  $[(0^\circ/60^\circ/-60^\circ)/(-60^\circ/60^\circ/0^\circ)]$
- 3 plies of 733 gsm Braid:  $[0^\circ]_3$  with tows staggered

To eliminate the boundary effects, the 12"x12" plaques were trimmed down by 0.5" from all four sides. DMA testing was used to determine the glass transition temperature ( $T_g$ ) of the molded material. Fiber Content, resin content and void content of the composites was determined using ASTM D3171 (Procedure G, Matrix Burn-off in a Muffle Furnace). Five specimens were used from each plaque to test the tensile and compressive properties of the molded plaques. Tensile properties, including ultimate tensile strength (MPa), strain at break (%) and tensile modulus (GPa), were determined by ASTM D3039, Tensile Properties of Polymer Matrix Composite Materials with tabbed specimens. This method is applicable to the determination of in-plane tensile properties of polymer matrix materials reinforced by high-modulus fibers (either continuous fibers or discontinuous fiber-formats in which the laminate is balanced and symmetric with respect to the test direction, e.g. braid and NCF specimens). Compressive strength (MPa) was determined by ASTM D6641, Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture, Procedure B (tabbed). This method is applicable to the determination of compressive strength and stiffness of polymer matrix materials in which the laminate is balanced and symmetric with respect to the test direction.

## MATERIAL PROPERTIES

Table 3 provides a synopsis of the novel attributes of a typical VORAFUSE™ P6300 prepreg. This product is a rapid cure system, curing within 3 minutes at 150 °C. The cured glass transition temperature ( $T_g$ ) of

the resulting molded composite is >150 °C. A Tg >150 °C allows a part compression molded at around 150 °C to be released while still hot without warping. That is, it enables parts to have sufficient integrity to be de-molded without first cooling the mold and part, which in turn enables shorter molding cycle times. In addition, a Tg >150 °C provides a composite material with the property of high heat distortion temperature which is needed for demanding applications.

**Table 3: Novel attributes of VORAFUSE™ P6300 prepeg**

<b>Storage</b>	Room temperature (25 °C) storage for up 30 days
<b>Automation</b>	Tack free handling
<b>Preforming</b>	Ultra-fast (< 1 min), automated preforming of complex shapes
<b>Molding</b>	Isothermal 150 °C compression molding
<b>Cure time</b>	Rapid processing, 2 minute cure time and no post cure
<b>Cured Tg</b>	155 – 165 °C (DMA)
<b>De-molding</b>	No external mold release required
<b>Handling</b>	Release paper free

Not only is this prepeg system fast curing under isothermal molding conditions, it also has a relatively long shelf life of 4 weeks at ambient temperature. VORAFUSE™ P6300 resin system is also formulated with an internal mold release agent which eliminates the need for frequent application of a release agent to the mold, thereby increasing productivity and reducing part cost.

The mechanical properties of molded composite plaques consisting of the 4 different fabric architectures were investigated.

#### **Density, Fiber Content, and Void Content**

Results from determination of density and fiber/resin/void content are summarized in Table 4. Very low void content of < 1.5 % was observed in all the fabric formats demonstrating the excellent infusibility of VORAFUSE™ P6300 resin system into a range of fiber areal weights and architectures.

**Table 4: Representative properties of composites molded from VORAFUSE™ P6300 prepeg using a range of reinforcement architectures**

Attribute	UD	2X2 Twill	NCF	Braid
Fiber content (wt %)	61	64.1	63.3	65
Density (g/cm <sup>3</sup> )	1.51	1.54	1.52	1.51
Void content (%)	1.2	1.4	1.4	1.4
Resin content (wt %)	39	35.9	36.7	35
Fiber content (vol. %)	53.9	54.1	52.6	55
Resin content (vol. %)	46.1	45.9	47.4	45

#### **Tensile and Compressive Properties**

The mechanical properties of the composite panels molded from VORAFUSE™ P6300 prepeg prepared from four different fiber architectures were evaluated through tensile and compressive testing in both longitudinal and transverse directions. Five specimens were tested for each condition. The results of the

tensile and compressive tests are summarized in Table 5. Comparison of the straight-sided tensile response indicated that as expected, the UD specimens consistently yielded the highest strength and stiffness when tested parallel to the axial fibers and the lowest strength and stiffness when tested perpendicular to the axial fibers. The tensile moduli and compressive properties of both the composites with  $0/\pm 60^\circ$  fiber reinforcement were found to be similar. However, the NCF fabric exhibited slightly higher tensile strength in both the longitudinal and transverse directions compared to the braided fabric. The data also showed that the  $[0^\circ, 90^\circ]$  2X2 twill has higher transverse tensile and compressive strength compared to the  $0/\pm 60^\circ$  fiber reinforcements oriented in a balanced layup.

**Table 5: Summary of tensile and compressive properties of composites molded from VORAFUSE™ P6300 prepreg reinforced with a range of CF fabric architectures**

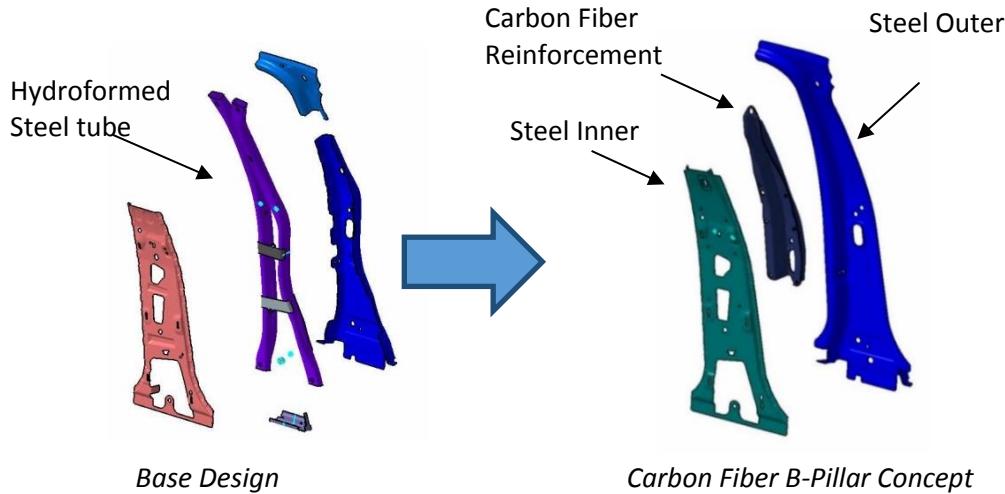
Property			UD	2X2 Twill	NCF	Braid
Part Thickness	mm		$2.64 \pm 0.16$	2.45	2.67	$2.27 \pm 0.05$
Glass Transition Temperature	°C	ASTM D5418 (DMA)	165	164	164	160
$0^\circ$ Tensile Strength	MPa	ASTM D3039	$1568 \pm 52$	$919 \pm 48$	$915 \pm 98$	$767 \pm 36$
$0^\circ$ Tensile Modulus	GPa		$127 \pm 8.5$	$65.5 \pm 3.9$	$68.6 \pm 8.4$	$77.6 \pm 4.9$
$0^\circ$ Tensile Elongation	%		$1.3 \pm 0.1$	$1.4 \pm 0.1$	$1.3 \pm 0.1$	$1.0 \pm 0.1$
$90^\circ$ Tensile Strength	MPa		$47.3 \pm 5.2$	$614 \pm 36$	$293 \pm 19$	$208 \pm 11$
$90^\circ$ Tensile Modulus	GPa		$8.4 \pm 0.9$	$58.8 \pm 3.8$	$36.2 \pm 2.8$	$36.6 \pm 2.9$
$90^\circ$ Tensile Elongation	%		$0.52 \pm 0.2$	$1.1 \pm 0.1$	$0.9 \pm 0.1$	$0.58 \pm 0.1$
$0^\circ$ Compressive Strength	MPa	ASTM D6641	$1149 \pm 65$	$650 \pm 93$	$631 \pm 87$	$631 \pm 53$
$90^\circ$ Compressive Strength	MPa		$167 \pm 7.5$	$474 \pm 71$	$250 \pm 12$	$239 \pm 14$

#### TECHNICAL DEMONSTRATION OF VORAFUSE™ P6300 PREPREG

The VORAFUSE™ P6300 prepreg technology was demonstrated on the B-pillar reinforcement for the Ford Fusion, shown in Figure 3.



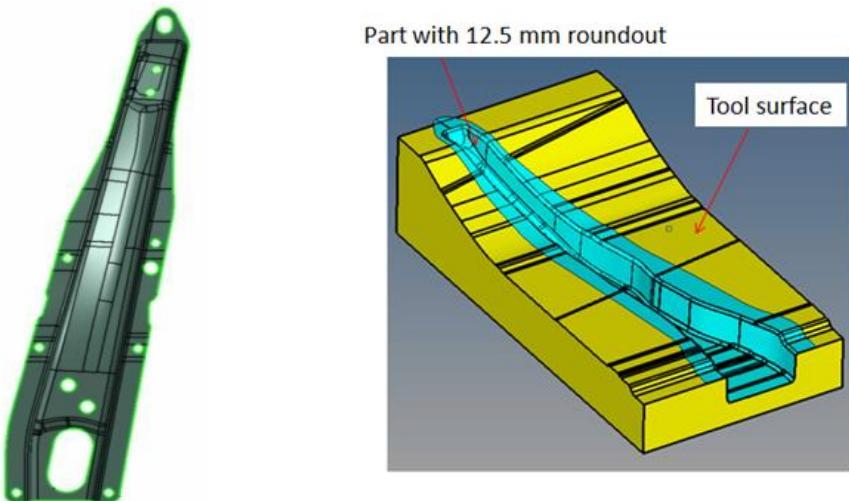
**Figure 3: Ford Fusion space frame with B-pillar highlighted**



**Figure 4: Ford Fusion B-pillar base-line design in comparison to a carbon fiber concept**

The existing B-pillar design is based on a metal sandwich structure with an integral hydroformed tubular high strength steel reinforcement. The application was deemed suitable to demonstrate the weight saving benefits of carbon fiber composites and the acceptability of these materials for structural applications. Figure 4 illustrates the baseline metal design in comparison to the optimized carbon fiber concept. This design achieved a significant weight saving of 14 lbs per vehicle.

Figure 5 depicts the B-pillar part design with a single part thickness of 3.9 mm. It has an overall channel design feature with a large open end and a small dome end as well as flanges with transitional “kinks” along its perimeter. In addition, there are discontinuous changes in height (or depth) between the main channel in the middle and the two ends. Besides the part design, tool surfaces are shown in Figure 6.



**Figure 5: B-pillar part design**

**Figure 6: Part and tool surfaces**

The [0°/60°/-60°] triaxial braid produced by A&P Technologies using DowAksa A42 carbon fiber content was chosen because it offers superior drapability, permeability and dynamic loading performance, as well as excellent static mechanical performance. The fabric was tailored to the B pillar longitudinal stiffness and strength design requirement while meeting cost targets.

Due to the tack free nature of the prepreg system, cutting was readily accomplished through an automated carriage-style XY cutting tables. Vacuum was applied to hold the prepreg in place. No release liner was required during cutting. Good cutting results were obtained with ultrasonic cutting tools. Cutting can also be accomplished with steel-rulled dies and a pneumatic (e.g. clicker) press.

After cutting of the prepreg plies, automated robotic handling was used to stack the plies into the required ply stack. Joining of the plies into a single consolidated ply stack was achieved through pre-heating, lamination, and cooling back to room temperature. Ultrasonic welding was utilized successfully to cause local melting of the prepreg resin formulation and consolidation of the plies, without any appreciable advancement of the prepreg Tg<sub>0</sub>.

A preform tool system (Figure 7) was used to form a thermally softened ply stack through mechanical action, rapid cooling, trimming of excess prepreg and then demolding a stable 3D preform at room temperature. A detailed cross-section of the tooling used to preform is illustrated in Figure 8. This preform process was used to successfully preform the prepreg based on the braided architecture in less than 60 seconds.

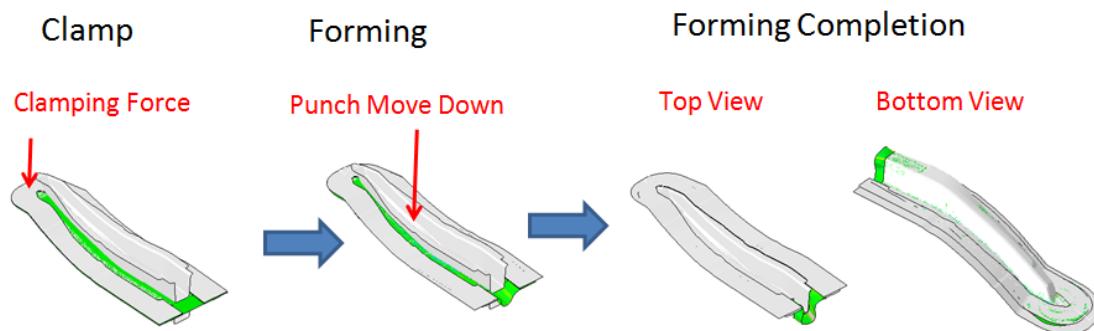
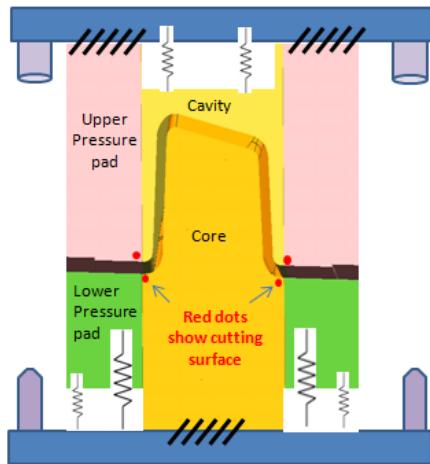


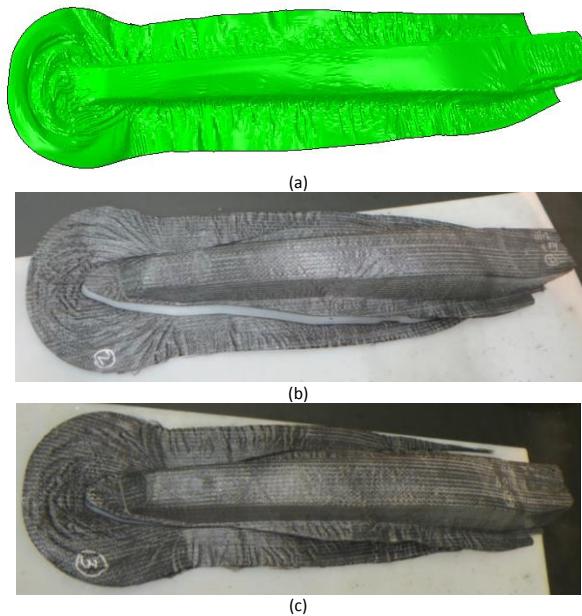
Figure 7: Forming schematic

Detailed formability analysis of the prepreg was completed and this data was utilized to develop FEA models that enable prediction of prepreg formability. Of particular utility is the ability to predict wrinkle formation and the impact of edge tension on resultant preform quality. Figure 9 compares the predicted shape at the end of the preforming simulation with the experimental results. As can be seen, the model captures the overall wrinkling pattern reasonably well regardless of the number of layers used in the experiment.



**Figure 8: Schematic of the B-pillar preforming tool.**

The preform was then compression molded. Cure time of the molding process can be adjusted based on tool temperature and desired degree of cure before mold opening. Application of external mold release was not required prior to the next molding cycle. Upon mold open, part can be removed via pneumatic or mechanical action. Figure 10 provides a photo of the preformed B-pillar and the subsequent molded part.



**Figure 9: Overall wrinkling pattern correlation: (a) model prediction, (b) experimental results using 4 layers of triaxial NCF prepreg, and (c) experimental results using 6 layers of triaxial braided prepreg**



**Figure 10: B-pillar preform (left) and molded B-pillar (right).**

Sub systems were built and tested for the static performance attributes summarized in Figure 11. Full vehicles were also constructed and tested to assess dynamic performance as illustrated in Figure 12.



Test	Base	CFRP
Door Slam Open Durability	Pass	Equal performance
Door Overload Open	Pass	Slight improvement
Door Drop Off and Sag	Pass	Equal performance
Striker Point Mobility	Pass	Significant improvement

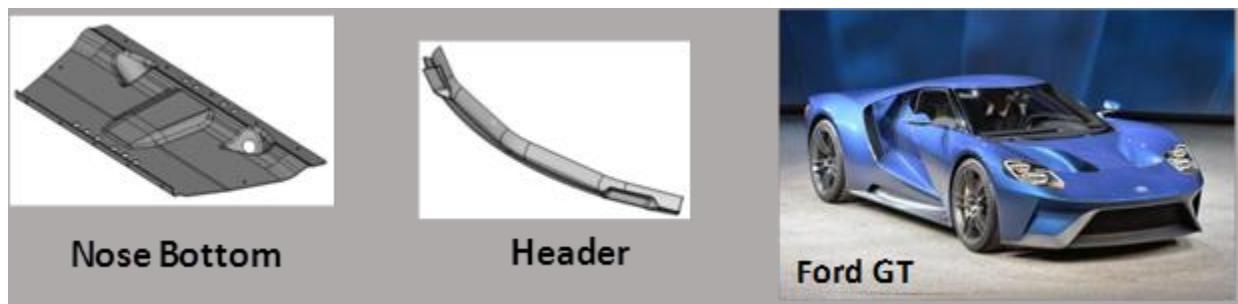
**Figure 11: Vehicle sub-system static performance**



**Figure 12: 50KM/h test showing pre- and post-test disposition of a vehicle built using the technology described in this paper**

### TECHNOLOGY DEMONSTRATOR – FORD GT

To demonstrate additional technical viability of this new material intermediate, Ford recently implemented this novel carbon fiber epoxy prepreg with support of their Tier 1 partner on the front roof header and nose bottom panel of the 2017 Ford GT. The same preforming and molding technology described above was utilized for both parts, as shown in Figure 13.



**Figure 13: Nose bottom and Header applications used as technology demonstrators on the 2017 Ford GT platform.**

### CONCLUSIONS

The on-going drive for improvements in vehicle fuel economy continues to spur new innovation in a wide array of vehicle technologies with vehicle mass reduction considered a critical element to achieving this

goal. The latter has prompted renewed interest in lightweight body and chassis systems that take advantage of advances in materials such as high strength steel, light metals and composites. This spurred a joint effort by Dow Automotive, Ford and DowAksa focused on the development and implementation of novel carbon fiber composites. The result of this joint development has yielded VORAFUSE™ P6300 prepreg, an epoxy based prepreg designed for high volume manufacture.

The hotmelt epoxy resin system described is well suited for infusion into a broad range of reinforcement architectures and areal weights. The low uncured glass transition temperature and very low viscosity of the resin system at infusion temperatures enables rapid impregnation into a variety of fabric reinforcements while minimizing void spaces within the prepreg. Prepreg materials with a range of reinforcement architectures, spanning fiber areal weights from 186 gsm to 733 gsm, all based upon the hot melt prepreg resin system were developed. High quality molded parts with low void content could be produced under identical isothermal molding conditions. The performance of these materials was validated in production processing scenarios culminating in full vehicle testing. As a result, Ford recently selected VORAFUSE™ P6300 for use in several components on the 2017 Ford GT.

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