CARBON FIBER: THE AUTOMOTIVE MATERIAL OF THE TWENTY-FIRST CENTURY STARTS FULFILLING THE PROMISE

Dale Brosius
Brosius Management Consulting

Abstract

For more than forty years since its introduction, carbon fiber composites have remained an elusive material in the automotive industry. Proven in jet fighters and high-end race cars for over 20 years, there is little doubt about its ability to build lighter, more durable vehicles. Offering a weight savings of 75 percent over steel, carbon fiber gives sports cars a real advantage in acceleration and top speed, and enables all automobiles to achieve improved fuel economy. Commercialization continues to be hindered by high material and processing costs and slow production rates. In spite of these obstacles, more than 25 series production vehicles will feature carbon fiber composites in 2004, fueled by advances in manufacturing technology, new material forms and steadily declining material costs. This paper presents the current state of carbon fiber use in automobiles in Europe, North America and Japan, ranging from the exotic "supercars" to niche producers and the major automobile manufacturers. Carbon fiber applications include body panels, structure and functional components. Advances in processing techniques will be reviewed, with a focus on what is being done today and what still needs to occur to economically move beyond volumes of a few thousand parts per year and into more mainstream vehicles.

Background

The selection of a material for an automotive application requires the evaluation of a number of specific criteria, including styling needs, performance demands, anticipated volumes, and ultimately, cost. Does each factor contribute positively to the business case for the vehicle? Can the preferred material and its associated manufacturing process be justified? What skepticism will have to be overcome via a thorough development and validation effort? Can we get this past the upper level decision makers? Will the consumer pay for it if it costs more to implement?

One material for which these questions have become increasingly relevant is carbon fiber. With over 40 years of use in military applications, and over 20 in high performance sporting goods, its appeal to automotive designers is stronger than ever. In the 2004 model year, over 25 vehicles will be offered for sale worldwide with OEM carbon fiber content. Does this mean carbon fiber has finally "arrived" as a viable material of construction for production automobiles?

The Promise

For several decades, producers of carbon fiber have attempted to get the material specified as a mainstream material for production vehicles. The raw fiber has a tensile modulus equal to steel at less than one-fourth the specific gravity. New developments in pitch-based fiber, produced from scrap material from the oil refining process, had the potential to yield fiber for less than several dollars per pound, the producers advertised. Spurred by the OPEC crisis of 1978, Ford built prototypes of the LTD, demonstrating weight savings of 544kg (1,200 lb) compared to the steel production model. With a manufacturing cost equal to that of a private airplane and a production process able to make one or two per day, the likelihood of this vehicle hitting the showroom floor was non-existent.

Fiber producers achieved moderate success in the 1980's with filament wound and pultruded drive shafts, but the economics did not justify widespread adoption. Pitch technology failed to deliver a low cost fiber, but significant advancements were made in lowering the cost of higher strength polyacrylonitrile, or PAN fibers, with the potential to get to below $5.00/lb for large volume commercial applications widely promoted. The price of carbon fiber in 2003, while not quite yet to $5.00, has reached a point where it has become a viable option for some vehicles.

Mass Savings Potential

Approximately 16% of the new 555 passenger Airbus A380 jumbo aircraft will be carbon fiber composites. Boeing has announced the fuselage and wings of the 7E7 under development will be carbon intensive to save weight. The use of carbon fiber in place of aerospace aluminum alloys is driven by the need to save weight in commercial aircraft, which translates to lower operating costs.

These same benefits are available to the automotive industry. Lower mass means better fuel economy, but it's first intrinsic advantage is an increase in acceleration and top speed, measures by which all sports cars are judged. Virtually all the world's "super cars," or those with a top speed exceeding 322 kilometers per hour (200 mph) and 0-100 kph (0-60 mph) times under four seconds, make extensive use of carbon fiber to attain these performance figures.

Continuous fiber composites, be they glass or carbon, have the ability to achieve directionally specific properties, a condition called *anisotropy*. This permits fibers to be preferentially oriented along the path of highest stress. The thickness can be locally tailored in high or low stress areas, something very difficult to do in stamped sheet metal. Optimally designed, continuous carbon fiber composites are 75 percent lighter than steel parts, 40 percent lighter than aluminum, and 50 to 60 percent lighter than fiberglass SMC. In body panels, thickness for carbon fiber composites typically range from 0.8 to 1.5 mm, similar to steel and aluminum sheet, and one-third to one-half that of other polymer-based composites at equivalent performance.

Sex Appeal

A major advantage of polymer composites over the bending of sheet metal is the ability to achieve radical styling – long, sweeping curves that improve aerodynamics and help the vehicle hug the road. Certainly, carbon fiber is associated with things that go fast – very fast, in machines like jet fighters, rockets and Formula 1 race cars. Carbon fiber is also linked to high performance sporting goods, such as golf clubs, tennis racquets, and Lance Armstrong's Tour de France bicycles. All America's Cup boats, and many other racing ships utilize carbon fiber extensively to remove weight above the waterline and achieve faster speed.

Putting carbon fiber onto a sports car delivers the same value to the driving enthusiast. It delivers a true performance advantage, and is still relatively rare, as there is a price premium involved. In some respects, the situation with carbon fiber today is similar to that of leather seating twenty years ago, a luxury not everyone can afford. In an application where the carbon fiber pattern is exposed and clear coated, the look is considered "high-tech."

Vehicle Differentiation

The composites industry has long touted the low investment cost of reinforced plastic processing, compared to sheet metal stamping, especially for low volumes. We are witnessing an ever-increasing fragmentation of build volumes in the automotive industry. Special editions, niche vehicles and consumer demand to own "something different" are driving demand for more composite parts. In some cases, this is as simple as adding a spoiler or changing the hood design on an existing high volume product; in others, it is creating an entirely new low-investment model.

Carbon fiber composites have lower tooling costs, in most cases, than even SMC and, when using epoxy prepregs are not subject to paint pops, which plague current SMC parts. For vehicle runs of up to 500 per year, low cost composite tooling generally suffices; for runs up to 1500 to 2000 per year, single sided metal molds are cost-effective. As fiberglass is no longer considered exotic, carbon fiber further enhances the differentiation.

Proven Durability and Toughness

Carbon fiber/epoxy composites have been proven in difficult service applications like military helicopters and jet fighters for over 20 years. The material has infinite fatigue strength, as long as strain values are kept to a reasonable level, such as 0.3%. Epoxy resins used have glass transition temperatures approaching, and in some cases exceeding 150ºC (300ºF), making them suitable for use in engine compartments and primary vehicle structure. In crash situations, carbon fiber has permitted many a race car driver to survive, indeed, in most situations, the ability to walk away from a high speed accident. Carbon fiber components used on production vehicles have successfully passed rough road durability, crash, simulated hail testing, and hot/cold slamming tests.

Production Vehicles Using Carbon Fiber

Europe

Europe is leading the way in the consumption of carbon fiber for automobiles, with a number of vehicles in production today or slated for production by early 2004 (Table I). The most visible of these are the 200 mph "super cars", including the Lamborghini Murciélago, Porsche Carrera GT and McLaren Mercedes SLR, all scheduled for production volumes of not 50 or 100 per year, but 500 per year. Considering that almost every body panel and, in the cases of the Carrera GT and SLR, the majority of the structure is carbon fiber, the volume consumed is quite attractive to material suppliers. However, these, plus the Ferrari Enzo (perhaps the fastest vehicle in production today, exist in a world where only performance counts, as each is priced above $275,000. In spite of these prices, demand for these vehicles easily outstrips supply (the Enzo sells for around $670,000 and Ferrari is very selective about who gets one).

In the U.K., a number of niche producers, including TVR, Invicta, Farboud and MG Rover are taking advantage of the low investment costs in tooling for carbon fiber composites. Each is also using new materials developed for vacuum bag cure only, eliminating the need for costly autoclaves.

Japan

Carbon fiber drive shafts, no longer in production in North America, have made a comeback in Japan. Up to 150,000 vehicles in 2004 will use lightweight, filament wound shafts from Toray Industries in place of steel shafts (Table II). Weight and cost are key drivers – for example, the Mazda RX-8 has a 1078mm (42.4 in) long shaft weighing 5.8 kg (12.8 lb), roughly 40 percent lighter than a two piece steel alternative with a center bearing.

The Mitsubishi Lancer Evolution VIII features a carbon fiber rear spoiler, produced via resin transfer molding (RTM). According to Mitsubishi, the new spoiler is about 2 kg (4.4 lb) lighter than the previous ABS spoiler and generates 1.7 times more downforce. The horizontal airfoil is also 60 percent slimmer than the ABS version. Mitsubishi is targeting sales of 5,000 units for 2004, likely making it the highest volume exterior carbon fiber auto part in production.

North America

All of the major U.S. auto companies have at least one vehicle in production or nearing production with some amount of carbon fiber (Table III). Each has also taken a different approach to implementing the material, with DaimlerChrysler favoring SMC processing for structural components and General Motors employing carbon fiber prepreg and stretching the capabilities of the autoclave process to reach 2,000 to 3,000 Class A hoods per year. Ford's first U.S. built vehicle incorporating carbon fiber will be the GT sports car, where autoclave-cured prepreg will be used for a structural inner panel (Ford's Aston Martin subsidiary in Europe has been in production of carbon fiber components for the Vanquish for several years using RTM).

Carbon Fiber Materials & Processing

Obtaining the performance advantages of carbon fiber can only be achieved when combined with a polymer resin system, or the "glue" that transfers the loads between the fibers and, when cured, forms the rigid shape of the part. This can occur inside the mold, as with resin infusion processes like RTM, or prior to molding, as with prepreg and SMC formats. While fiber prices have declined substantially, converting the fiber into finished parts continues to be very costly. These processing costs are a major barrier to growth for carbon fiber composites.

In the current market for carbon fiber automobiles, preimpregnated tapes and fabrics (prepregs) are the dominant form of starting material. A primary reason for this is these materials have become the standard for building open wheel racing vehicles, such as Formula 1, IndyCar and CART, and the design techniques for these vehicles can also be applied to high performance sports cars. Prepregs have inherently higher fiber volumes (typically 50 to 60 percent) than wet layup methods, resulting in higher stiffness at lower weight. Prepreg technology was developed initially for the aerospace industry, and the materials offer very tight control of resin content and fiber areal weight, resulting in consistent, predictable properties and cured ply thickness.

The most common technique for producing parts with prepreg involves the cutting of individual plies to a flat shape representation of the finished part and laminating, layer by layer onto a one-sided mold. This offers considerable flexibility in fiber orientation, localized thickness changes, and mixing of material types. Once layup is complete, the laminate is covered with separator film, a breather fabric (to allow air to escape), and a sealed vacuum bag is placed over the mold. While vacuum removes air from the laminate, external pressure, typically 4 to 7 bars (60 to 100 psi), is applied in a pressure vessel called an autoclave. This additional pressure collapses any remaining air bubbles and yields a void volume content typically under two percent. The surrounding air (or nitrogen) inside the autoclave is raised to a programmed cure temperature (nominally 121 to 177ºC, or 250 to 350ºF), followed by a hold period at temperature and cooling of the mold to a temperature safe enough for people to remove the part and repeat the process.

In the aerospace environment, cure cycles of 20 hours are not uncommon, and cycles of 5 to 10 hours are typical (including heating and cooling steps) for Formula 1 and supercar components. As rates of one to two per day are sufficient to meet vehicle build rates, relatively little focus has been placed on reducing cycle time. The current roster of significant prepreg suppliers to the automotive industry, including Cytec, Hexcel and Toray, are also the three largest suppliers of prepreg to the aerospace industry.

Curing of prepregs via autoclave is expensive and very rate limited. The capital and operating costs for autoclaves are high, and the hand laminating process labor intensive. Several efforts have been launched to address these issues. The 2004 Corvette Z06 Commemorative Edition hood is being produced using a resin system from Toray designed to cure in under 10 minutes at 150ºC (300ºF). The cure cycle has been reduced to a total of approximately two hours, yet over 90 percent of this time is spent heating and cooling the mold. The molder, MacLean Quality Composites has developed a manufacturing process which performs most of the layup steps outside the mold, permitting simultaneous cure on one part while the next one is being prepared. A "prepreg preform" is quickly positioned in the empty mold, permitting increased production.

Several suppliers of advanced composite materials have introduced products that may eliminate the need for autoclave pressure to attain a Class A surface. These take the form of semi-impregnated sandwiches of dry fabrics and interleaved resin films, which allow the air in the laminate to escape prior to the resin melting and wetting out the fabric. Essentially a form of resin film infusion, these products, including SPRINT from SP Systems and Z-PREG from Advanced Composites Group, are designed to yield void-free laminates and a Class A surface when combined with a surfacing film under vacuum consolidation only. Cure times are roughly one hour hold at 121ºC (250ºF), possible with a simple oven.

For structural components, the use of textile performing technologies like braiding and multi-axial heavy fabrics can be combined with liquid molding techniques, such as RTM and SRIM. Success with using liquid molding for class A body panels is rather limited to this point, and minimum thickness requirements to facilitate resin flow may limit application. Both BMW and Aston Martin (Ford) have implemented RTM for production of carbon fiber parts.

While fiberglass SMC is used quite extensively for the production of exterior body panels, carbon fiber SMC has not yet demonstrated this capability. Use in complex structural parts should grow, in applications similar to those on the Dodge Viper, partly due to the use of the familiar compression process and fairly fast cycle times. Again, minimum thickness requirements of approximately 2.0 mm (0.080 in) to achieve good parts will negate some of the weight savings possible for lightly loaded components.

Most of the carbon fiber parts produced in Europe are formed on composite molds, due to relatively low build rates. These molds have a life span of hundreds of cycles for typical parts, and perhaps one thousand for simple geometries. In the commercial aerospace industry, molds produced from steel and Invar (a nickel-iron alloy with near-zero coefficient of thermal expansion like carbon fiber composites) have replaced carbon composite molds for full scale production. Invar molds are being used for the production of the Corvette hoods, and should be suitable for years of aftermarket use once model production is complete.

Opportunities & Challenges

Has carbon fiber finally "arrived" in the automotive industry? The interest in the material and its use is at unprecedented levels, but sizable hurdles remain. Although the material costs have declined to more attractive levels, the conversion costs to turn such materials into finished parts are stubbornly high, resulting in part prices of $55 to $220 per kilogram ($25 to $100 per pound).

It will not be necessary to achieve costs as low as steel parts, or even fiberglass SMC, for some use of carbon fiber to take hold. Consumers have demonstrated they will pay significant premiums to drive large vehicles like SUV's and luxury cars, and the market is demanding more horsepower and performance in both sports cars and everyday vehicles. If CAFE requirements are raised, carbon fiber composites, while expensive, are quite effective in achieving mass reduction and improving fuel economy without sacrificing size or acceleration. Increasing demand for carbon fiber should continue to drive innovations in manufacturing.

Lightweight structures and body panels will be essential to achieving the desired performance and range of fuel cell vehicles. Whether such structures will be composite or metal is yet to be determined, and certainly there are considerable other technical problems to be resolved regarding fuel cell vehicles before body structures are considered. Nonetheless, if these issues are solved, fuel cell cars represent a sizable opportunity for carbon fiber.

The supplier community needs to address other issues. Further automation in shaping and curing of carbon fiber composites will be required to improve product quality and remove direct labor costs. Elimination of autoclave curing, either through improvements in materials, or the development of standalone cells capable of quickly heating and cooling the material, should result in lower capital and operating costs. Sharing a problem with fiberglass composites, the material and performance database needs to be expanded, so that automotive engineers can specify carbon fiber composites with confidence. It is effort in this last area that will produce the most immediate expansion of the application base.

Tables & Figures

Table I: 2004 Model Year European Vehicles with Significant Carbon Fiber Content

EUROPEAN VEHICLES WITH CARBON FIBER CONTENT (2004 MODEL YEAR)		
VEHICLE	**VOLUME**	**CARBON FIBER COMPONENTS**
Lamborghini Murcielago	550/year	Body panels, some structure (autoclave cure)
Ferrari Enzo	399 over 3 years	Body panels and structure (autoclave)
Pagani Zonda	20/year	Body panels and structure (autoclave)
Edonis BEX38	21 over 3 years	Cockpit structure (autoclave)
Porsche Carrera GT	1500 over 3 years	Body panels, structure, engine subframe (autoclave)
Mercedes SLR	500/year	Body panels and structure (resin infusion, vacuum cure of semi-preg)
Aston Martin Vanquish	300-400/year	A pillars, tunnel, front crash structure (RTM, braided and stitched multiaxial preforms)
BMW M3 CSL	1,000/year	Roof, front air dam, rear spoiler (RTM)
TVR Tuscan R	50/year	Body panels (vacuum cure of semi-preg)
MG X-Power SV	250/year	Body panels, some structure (vacuum semi-preg)
Invicta S1	<50/year	Body panels, some structure (vacuum semi-preg)
Farboud GTS (body panels)	<50/year	Body panels (vacuum semi-preg)
Morgan Aero 8	approx. 300/year	Removable hardtop (vacuum semi-preg)
Ronart Lightning	<50/year	Body panels
Koenigsegg CC	<50/year	Body and structure (autoclave)
Bristol Fighter	<50/year	Doors and tail gate

Table II: 2004 Model Year Japanese Vehicles with Significant Carbon Fiber Content

JAPANESE VEHICLES WITH CARBON FIBER CONTENT (2004 MODEL YEAR)		
VEHICLE	**VOLUME**	**CARBON FIBER COMPONENTS**
Nissan 350Z	30,000-50,000/year	Drive shaft (filament wound)
Mazda RX-8	40,000-60,000/year	Drive shaft (filament wound)
Mitubishi Pajero/Montero	50,000-70,000/year	Drive shaft (filament wound)
Acura NSX-R	<200/year	Hood (autoclave), rear spoiler (RTM)
Nissan Skyline GT-R Vspec	<200/year	Hood (RTM)
Mitsubishi Lancer Evolution VIII	5,000/year	Rear spoiler (RTM)
Dodge Viper SRT-10	300-400/year	Windshield frame, front end structure, door panels (carbon fiber SMC)
Chevrolet Corvette Z06	2,000-3000	Hood (autoclave outer, SMC inner)
Saleen S7 (body panels)	up to 100	Body panels (autoclave)
Ford GT (rear decklid inner)	4,500 over 3 years	Rear engine cover inner panel (autoclave)

Table III: 2004 Model Year North American Vehicles with Significant Carbon Fiber Content

NORTH AMERICAN VEHICLES WITH CARBON FIBER CONTENT (2004 MODEL YEAR)		
VEHICLE	**VOLUME**	**CARBON FIBER COMPONENTS**
Dodge Viper SRT-10	2,500/year	Windshield frame, front end structure, door panels (carbon fiber SMC)
Chevrolet Corvette Z06	2,000-3000	Hood (autoclave outer, SMC inner)
Saleen S7 (body panels)	up to 100/year	Body panels (autoclave)
Ford GT (rear decklid inner)	4,500 over 3 years	Rear engine cover inner panel (autoclave)

Figure 1: The Porsche Carrera GT is highly carbon-intensive, with body panels and structure produced from autoclave-cured epoxy prepreg.

Figure 2: MG Rover X-power SV contains 36 carbon composite components. Structural parts are autoclave cured, while body panels use a vacuum-cured “semi-preg” system.

Figure 3: Braiding and other preforming techniques are used in the RTM carbon fiber A-pillars, transmission tunnel and front crash structure of the Aston Martin AM-12 Vanquish.

(Photos courtesy of each respective OEM)

Figure 4: Optional carbon fiber rear spoiler on the Mitsubishi Lancer Evolution VIII is produced via RTM

Figure 5: The Dodge Viper SRT-10 marks the first production use of carbon fiber SMC, using the material in the front end structure, windshield surround and door inner panels.

Figure 6: Chevrolet Corvette Z06 Commemorative Edition vehicles will carry an autoclave-cured carbon fiber hood in 2004, the first use of exterior Class A carbon on a North American mainstream vehicle.