Carbon Fiber Reinforced Composites and the Automotive Industry: A New Frontier?

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SUMMARY: Over the past fifty years, composites have become accepted in the automotive industry as an alternative material to steel for the production of exterior closure panels, semi-structural and structural parts. Composite components can now be found across the entire gamut of vehicles produced by the automotive industry including passenger, sports, and luxury cars, light- and medium-duty trucks, sport utility vehicles, and mini-vans. The vast majority of these composites are reinforced with either short or chopped glass fibers and they provide weight savings of 15 - 30% relative to a comparable steel part. As the automotive industry strives to improve fuel economy and reduce emissions of future vehicles, greater weight savings are needed. Aluminum and magnesium offer mass savings relative to steel of 50 - 60%. For composite materials to compete with these lightweight metals, carbon fiber must be utilized as the reinforcing fiber. This paper will present the preliminary results of experimental studies into the use of chopped carbon fiber in sheet molding compound (SMC) and structural reaction injection molded (SRIM) composites. While cost is a long-term business issue that will affect the proliferation of carbon fiber composites in the automotive industry, these studies have shown that technical issues including the fiber form and surface treatment exist that affect chopping, molding, and performance of carbon fiber reinforced composites. These technical issues must be addressed if carbon fiber composites are to become a viable alternative to aluminum and magnesium.

KEYWORDS: Carbon Fiber, Sheet Molding Compound, Preforming, Structural Reaction Injection Molding, Automotive.

INTRODUCTION

Over the past fifty years, composites have become accepted in the automotive industry as an alternative material to steel for the production of exterior closure panels, semi-structural and structural parts. Composite components can now be found across the entire gamut of vehicles produced by the automotive industry including passenger, sports, and luxury cars, light- and medium-duty trucks, sport utility vehicles, and mini-vans. Relative to steel, composite materials provide the automotive industry with a variety of benefits including parts consolidation, design/styling flexibility, corrosion resistance and lower capital investment. The vast majority of these composites are reinforced with either short or chopped glass fibers and they provide weight savings of 15 - 30% relative to a comparable steel part. As the automotive industry strives to improve fuel economy and reduce emissions of future vehicles, greater weight savings are needed. Aluminum and magnesium offer mass savings relative to steel of 50 - 60%. For composite materials to compete with these lightweight metals, carbon fiber must be utilized as the reinforcement. Thus, this paper will present the preliminary results of experimental studies into the use of chopped carbon fiber in sheet molding compound (SMC) and structural reaction injection molded (SRIM) composites.

CHOPPABLE CARBON FIBER

Carbon fiber rovings are typically single-ended type materials as they have traditionally been used in fiber conversion processes such as weaving, braiding, stitch bonded fabrics, and pre-preg manufacture or in composite fabrication processes such as pultrusion and filament winding. This presents a problem for the automotive industry. Specifically, the automotive industry uses large quantities of compression molded SMC and SRIM composites because of the low investment associated with these processes relative to steel stamping and the fast cycle times (i.e., 1 - 4 minutes). Historically, these materials and processes have employed a multi-ended glass fiber roving, which is an entirely different product form, as it chopped during the compounding stage for SMC or during the performing stage for SRIM. Although several carbon fiber roving variants have been and are currently under development at several suppliers, they all seem to fall short of optimum when compared to glass fiber rovings designed for chopped fiber applications. As a result, a myriad of processing issues exist when attempting to fabricate carbon fiber sheet molding compound (CF-SMC) or carbon fiber preforms for SRIM such as fiber fuzzing, substantial fiber ‘fly’ and excessive filamentization of the chopped material.

CARBON FIBER REINFORCED SMC COMPOSITES

In 2002, the North American transportation industry (i.e., automotive and heavy truck) consumed over 200 million lbs. of SMC [1]. The formulation of this material can be tailored to meet the demands of the application (i.e., Class "A" body panel, under-the-hood component or structural part). For structural applications, vinyl ester resins are typically used to meet the operating temperatures and 50% by weight, glass fibers are used as the reinforcement to provide the stiffness and strength required. To achieve the greatest weight savings relative to steel, the initial studies on CF-SMC have replaced all of the glass fiber with carbon fiber.

To fabricate the test panels for this study, single-ended 12K PAN carbon fiber SMC was compounded on a conventional line and maturated in a temperature and humidity controlled room. After thickening to the desired viscosity, plies of a pre-determined size and shape were cut from the roll and stacked up to form the charge. The charge was then placed onto the core of the tool and compression molded into test plaques.

Tensile and compression tests were performed on specimens machined from the composite plaques in both the 0^o (parallel to the compounding machine) and 90^o (cross the compounding machine) directions and the results are provided in Table 1.

To put this data into perspective, it should be noted that this material was reinforced with 55% by weight carbon fibers resulting in a composite with a specific gravity of 1.5. The data in Table 1 clearly indicates that there is a significant amount of variability in the CF-SMC as the coefficients of variation (COVs) ranged between a low of 9% and a high of 21%. In some cases (most notably tensile modulus and compressive strength), the CF-SMC exhibits anisotropy. With the amount of scatter in the data, it is hard to determine how real this phenomenon is or if the 0^o and 90^o data overlap. However, if an automotive design approach (typically mean minus three standard deviations) is used, the combination of the COVs and the anisotropy dramatically decreases the design allowable. Finally, by comparing the properties in Table 1 to those of 50% by weight glass fiber reinforced SMC [2], it is clear that the use of carbon fiber substantially increases the tensile modulus but there is much less of a benefit of incorporating this reinforcement in terms of increasing tensile and compressive strengths.

Table 1: Mechanical properties of CF-SMC *

Property	Carbon Fiber SMC	
Test direction	0^o	90^o
Tensile modulus, GPa	43 (21%)	36 (14%)
Tensile strength, MPa	212 (19%)	205 (12%)
Poisson's ratio	0.26	0.40
Compressive strength, MPa	234 (11%)	292 (9%)

** The data in parentheses is the coefficient of variation associated with the property.*

CARBON FIBER REINFORCED SRIM COMPOSITES

For this portion of the study, chopped carbon fiber performs were fabricated using the Ford Programmable Preforming Process (F3P) and then molded into a composite via SRIM with a polyurethane resin. With the F3P process, carbon fiber rovings were processed through an Aplicator SMART chopper gun and a flat panel preforming tool was used for preform fabrication. The flat panel preforming tool is 700 x 700 mm and the consolidation thickness can be varied with the use of stop blocks at the four corners of the tool.

For these experiments, a total of three different materials were tested: two carbon fiber rovings and one glass fiber roving. The experimental carbon fiber rovings tested are designated as Carbon Roving A and B. Carbon Roving A is a multi-ended roving containing a total of approximately 48k filaments that have been split into 8 bundles containing approximately 6k filaments per bundle. Carbon Roving B was also a multi-ended roving but it contained a total of 36k filaments by combining 12 bundles with each containing 3k filaments. The glass fiber used was a gun roving, which is mainly used in the spray-up process, but it has also been successfully used in chopped fiber performing processes.

During visual examination of the carbon fiber preforms fabricated at low areal densities (<1000 g/m^2), it was noticed that an excessive amount was light transmitted through the perform.

When these performs were placed on a light table (Figs. 1 and 2), it was evident that regions of zero fiber content were present. This phenomenon was not evident in glass fiber preforms fabricated at areal densities yielding the same fiber volume fraction. Based upon these visual issues, preliminary screening experiments were conducted in an attempt to determine what factors contributed to the formation of the zero fiber regions. The results of these studies indicated that preform processing parameters did not contribute significantly and, therefore, could not be used to reduce the amount of zero content regions within the preform. The main factor was determined to be the particular type of carbon fiber roving used in preform fabrication with Carbon Roving A being the worst case. If regions of zero fiber existed, then in order to maintain the overall areal density within the plaques, regions far exceeding the nominal were also present.

Fig. 1: Carbon Roving A @ 500 g/m^2

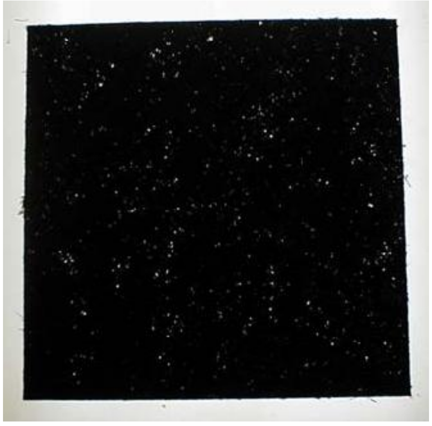

Fig. 2: Carbon Roving A @ 1000 g/m^2

In addition to the light transmission study, the perform permeabilities were also measured by using Darcy's Law in a rectilinear permeability rig. Three pressure transducers were used to obtain pressure data and are located at 33, 115 and 218 mm from the injection point. The fluid used was a mixture of 82% by weight glycerol and 18% by weight water with a viscosity of approximately 56 mPa·s. Pressure data between the three transducers was used to calculate the permeability. All preforms were fabricated using the same preform processing conditions yielding a fiber volume fraction of 40% for a 3.0 mm cavity thickness. This corresponds to a preform areal density of 2160 g/m^2 for carbon fiber and 3072 g/m^2 for glass fiber.

As shown in Table 2, the preform with Carbon Roving B exhibits decreased permeability when compared to the preform with Carbon Roving A. This is probably caused by the increased number of individual bundles present within the preform. This provides an increased number of fiber contact points and an overall increased surface area for fluid contact thereby increasing the resistance to flow and yielding lower permeability. Conversely, the permeability of the glass fiber preform is comparable to that of Carbon Roving A; however, the glass fiber roving contains approximately 12 times as many bundles as Carbon Roving A. Based on the permeability data and the differences highlighted above, it is believed that as carbon fiber rovings approach bundle geometries comparable to glass fiber rovings, which is necessary for uniform fiber dispersion, the permeability of carbon fiber preforms will be substantially lower when compared to glass fiber preforms.

In terms of mechanical testing, tensile tests were performed on specimens machined from SRIM composite plaques formed with Carbon Roving A as well as the baseline glass roving. By comparing the properties of these materials (Table 3), it is clear that the use of carbon fiber almost doubled the tensile modulus; however, the use of carbon fiber actually led to a decrease in both the tensile strength and strain to failure. The authors attribute these results to the findings of the light transmission studies in which high and low areal density regions were found in performs with carbon roving A. This also explains the greater variability in the CF-SRIM composites as the COVs were greater than those measured for the glass fiber-SRIM composites.

Table 2: In-plane permeabilities of chopped, random fiber preforms

Material Type	Thickness (mm)	Fiber Volume Fraction (%)	Wetted In-Plane Permeability (Darcy)	COV (%)
Carbon Roving A: 8 x 6k	3.0	40	145	27
Carbon Roving B: 12 x 3k	3.0	40	59	25
Glass Roving OC 357 D-AA	3.0	40	125	21

Table 3: Mechanical properties of glass and carbon fiber reinforced SRIM composites *

Property	Polyurethane/Glass Fiber	Polyurethane/Carbon Fiber
Fiber volume fraction, %	38	40
Tensile modulus, GPa	15.2 (8%)	27.9 (22%)
Tensile strength, MPa	247 (12%)	200 (13%)
Tensile strain, %	2.30 (7%)	0.80 (17%)

** The data in parentheses is the coefficient of variation associated with the property.*

SUMMARY

As the automotive industry strives to improve fuel economy and reduce emissions of future vehicles, greater weight savings are needed. Aluminum and magnesium offer mass savings relative to steel of 50 - 60%. For composite materials to compete with these lightweight metals, carbon fiber must be utilized as the reinforcing fiber. This paper presented the preliminary findings of experimental studies into the use of chopped carbon fiber in SMC and SRIM composites. While cost is a long-term business issue that will affect the proliferation of carbon fiber composites in the automotive industry, these studies have shown that technical issues also exist. Specifically, the variability and anisotropy in the CF-SMC must be reduced and the chemistry must be optimized in order to improve the adhesion of the vinyl ester resin to the carbon fibers in order to increase the tensile and compressive strengths. With regards to CF-SRIM composites, a great deal of improvement is needed to reduce variability within carbon fiber preforms to levels normally associated with glass fiber.

Based upon the test results presented, it appears that with an improvement to the product form, preform characteristics can also be improved to benefit not only the preforming process but also the molding process and mechanical performance of composite.

REFERENCES

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