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MANUFACTURING OF TRANSPARENT COMPOSITES USING VACUUM INFUSION PROCESS

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ABSTRACT

Glass is the most commonly used transparent material. However, glass is not suitable in applications where low weight, high strength and complex profile shapes are required. For many applications there exists a need for mechanically strong composite materials of high optical quality and transparency equivalent to window glass. Glass fiber reinforced transparent composite is a viable solution. A novel optically transparent glass fiber reinforced polymer matrix composite has been developed by infusing a clear epoxy resin system of matching refractive index into a stacked glass fabric preform. Transparent composites are manufactured using a low cost, environmentally friendly vacuum infusion process. Conventional low cost E-glass fibers are used as reinforcement. Physical and mechanical tests have been conducted. Results indicate that the transparent composites possess good physical and mechanical properties.

1. INTRODUCTION

Composite structures are increasingly being used in a wide variety of applications due to their high specific strength and modulus [1]. Even though uses of composite structures can range from such fields as marine and automotive to skis and tennis rackets, their great strength-to-weight ratio makes composites ideal for aerospace applications [2]. Glass has been commonly used for windows in airplanes because of its hardness, chemical inertness, abrasion resistance and relatively low costs. However, glass is brittle, heavy, shatters upon impact and difficult to form complex shapes. Light weight and mechanically strong alternatives are highly desirable. Optically transparent composite is a viable solution. Transparent composites can replace traditional heavy glass on the airplanes with light weight windows and windshields [3-4].

A transparent composite is based on the concept of matching the refractive index of the glass fiber with that of resin [5]. Refractive index of the matrix can be modified to match with that of the glass fiber by changing the degree of polymerization of the polymer matrix. Various processing factors such as the amount of initiator, cross-linker, curing temperature and time must be carefully controlled to obtain a given refractive index. Another method is to use a polymer matrix with its given refractive index and to modify the refractive index of the glass fiber. The refractive index of the glass fiber depends on its chemical composition, thermal history and fiber diameter. The diameter of the glass fibers pulled from a crucible of constant geometry depends upon the glass flow rate through the nozzle and the velocity at which the fibers are drawn by a take up wheel. Annealing can also increase the refractive index of chilled glass and could be potentially useful in fabricating transparent composites. A proprietary thermoset epoxy resin has been developed at Missouri S&T and is used as the matrix. The resin has a low viscosity which allows it to be utilized in various liquid composite manufacturing processes.

Low cost raw materials and fabrication process, comprising major portion of the final cost of the composite, are ideal. Hence E-glass and vacuum assisted resin transfer molding (VARTM) process are selected. The traditional VARTM process has been modified according to the requirements of optical transparency of composites. The VARTM process offers several advantages over conventional composite manufacturing methods such as lower tooling cost, net shape manufacturing of large complex parts and low emission of volatile chemicals [6]. Manufacturing of quality parts using the vacuum infusion process is dependent on various parameters such as viscosity of the resin, permeability of the preform, location of resin inlet, and vacuum ports [7]. VARTM utilizes vacuum as the driving force to pull the resin through the stacked preforms. In vacuum infusion process, glass fiber preform is placed on to a one-sided mold and the mold is vacuum sealed with a flexible bag. Resin is then drawn into the mold by vacuum pressure to impregnate the preform.

Several concepts of transparent composite were reported in literature. Olson et al. proposed transparent composite with glass reinforcements in thermoplastic PMMA matrix [8]. Kagawa et al. manufactured mixing glass powder with the epoxy resin [9]. Specialty rectangular glass ribbons were used as reinforcements by Chandrashekhara et al. [5]. Wilenski et al. studied multiple density glass fibers in a polymeric matrix [10].

In the present work, a new class of composite materials is demonstrated using conventional E-glass and low cost manufacturing method. The cured parts were tested for density, fiber volume fraction, tensile and flexural properties. These tests show that the transparent composites posses good physical and mechanical properties. These new glass fiber reinforced structural transparent composites will find applications in windshields, windows and other components where a strong, lightweight transparent material is desirable. Transparent composites will also have potential applications as backing material in transparent armor systems.

2. MATERIALS

A clear epoxy based one part resin system with refractive index matching the glass fibers has been developed at the Missouri University of Science and Technology. This resin system has been tailored to have a low viscosity thus enabling it to be used in a wide range of composite manufacturing processes. Bi-directional (0°/90°) woven glass fabric from Owens Corning Composite Materials, LLC, OH were used as fiber reinforcements.

3. MANUFACTURING

Manufacturing of the transparent composite was accomplished by the use of vacuum infusion process. The process uses a single sided tool and a flexible vacuum bag. The schematic of a typical VARTM process is shown in Fig. 1. The infusion of resin into the fabric can be influenced by the permeability of the preform, the fiber architecture, and the presence of fabric crimping.

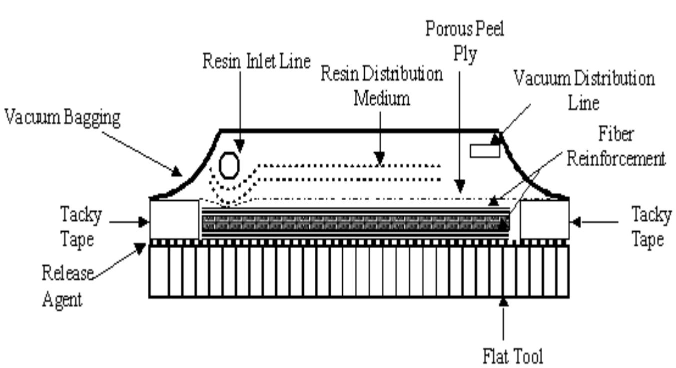

Figure 1. Schematic of a Typical VARTM Process

The first step in the manufacturing process is to prepare the mold. The mold is thoroughly sanded to remove any scratches and cleaned using solvents and cotton cloths. The glass fibers are then laid on the mold. The resin inlet and vacuum lines were positioned and then the preform was placed in a vacuum bag which was sealed around its perimeter with a general use tacky tape. The vacuum and resin inlet lines are placed on the opposite sides of the fiber squares. The mold is then vacuum-bagged. The vacuum line is connected to a vacuum pump and the mold is checked for leaks. Any leaks which are found must be sealed. Once the mold preparation is complete, the resin is degassed and heated to approximately 120 ˚F which lowers the viscosity. The mold is also heated to 120 ˚F. The lower resin viscosity allows the resin to infuse more easily. The degassed resin is now allowed to flow through the inlet line. The resin will slowly infuse through the part. The infusion process can take approximately thirty to forty-five minutes to complete. Once the part is fully infused, both the inlet and vacuum lines are shut off.

The cure cycle for manufacturing a transparent composite with vacuum infusion contains multiple parts. The part must be heated to 175 ˚F for 16 hours. Both the inlet and vacuum lines should be completely shut off throughout the cure cycle. This keeps the infused resin within the part and prevents voids from forming within the part which in turn will affect the transparency of the finished composite. Once cured, the part can then be post cured. The process involves heating the mold to 250 ˚F for 2 hours. The cure cycle used for the part manufacturing is shown in Fig. 2. After the completion of post cure cycle, the mold is cooled to room temperature and the part is separated from the mold.

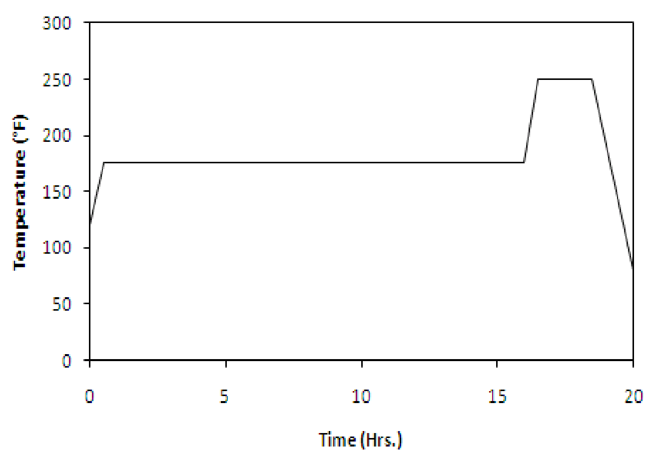

Figure 2. Cure Cycle

The part would then be examined for voids, surface finish, and how well the refractive indices matched. Figure 3 shows a partially infused composite showing both transparency of manufactured portion against the opaqueness of non-infused portion. Figure 4 shows the comparison of the transparent composite versus a normal glass plate.

Figure 3. Partially Infused Panel

Figure 4. Transparent Composite (Left) vs. Glass Plate (Right)

4. PERFORMANCE EVALUATION

4.1. Fiber Volume Fraction

Fiber volume fraction tests were performed according to the ASTM 3171 nitric acid digestion method. Four coupons, each weighing between 0.5 to 1.0 gm were randomly cut from the panels. The edges of the coupons were polished to allow for more precise measurements. The coupons were dried for over 1 hour at 300˚F to remove any moisture present on the surface of the coupon. The coupons were then placed in a container filled with concentrated nitric acid. The container was heated at 176˚F for 6 hours. Figure 5 shows the testing setup.

Figure 5. Fiber Volume Fraction Test Setup

Once the resin matrix was completely digested, the specimens were washed with water and acetone to remove any remaining acid. The specimens were then dried in an oven at 212˚F for 1 hour. The fiber volume fraction was calculated with equation:

$$V_f = \frac{M_f \times D_c}{M_c \times D_f}$$

where, Mc is mass of the laminate specimen,
M_f is mass of fiber in the specimen,
D_c is density of the composite, and
D_f is the fiber density.

The composite panels have an average fiber volume fraction of 40.3%. Table 1 lists the fiber volume fraction for the transparent composites.

Table 1. Fiber Volume Fraction Test Results

Specimen	Density (g/cc)	Fiber Volume Fraction (%)
1	1.7566	40.48
2	1.7589	40.34
3	1.7496	39.94
4	1.4799	40.34
Average	1.6863	40.28

4.2. Tensile Tests

Tensile tests were conducted on both neat resin samples and transparent composite samples. The tests were performed in accordance with ASTM D3039 on an Instron test machine. Figure 6 shows a sample being tested. Attached to the sample is the extensometer used to measure strain. Five specimens were tested. The tests were executed at a cross head speed of 0.05 in/min, in accordance to ASTM standards.

Figure 6. Composite Sample Undergoing Tensile Testing

Table 2 lists the tensile modulus, tensile strength, and the failure strain of neat resin and composite samples. The neat resin had an average tensile modulus of 3.17 GPa and a tensile strength of 46.75 MPa. Composites had a tensile modulus of 31.74 GPa and a strength of 374.9 MPa. The tensile modulus and strength for the composite panels are much higher than the modulus and strength of the neat resin. This was to be expected since the fibers carry most of the tensile load.

Table 2. Tensile Test Results

	Tensile Strength (MPa)	Tensile Modulus (GPa)	Strain to Failure (%)
Neat Resin	46.75	3.17	2.14
Composite	374.9	31.74	1.84

4.3. Flexure Tests

Neat resin and composite panels were tested for their flexural modulus and strength on an Instron machine in accordance with the ASTM D-790 standard test. The flexure specimens were 6 in x 0.52 in x 0.04 in with a span of 2 inches. The crosshead speed was 0.1 in/min. Five specimens were tested. Figure 7 shows a sample during the flexural test.

Figure 7. Composite Sample during Flexural Test

Table 3 lists the results from the flexural tests. The tests indicated that the neat resin samples had a flexural strength of 125.3 MPa and a flexural modulus of 4.28 GPa whereas, composites had a flexural modulus of 19.01 GPa and a flexural strength of 629.7 MPa.

Table 3. Flexural Test Results

	Flexure Strength (MPa)	Flexural Modulus (GPa)	Strain to Failure (%)
Neat Resin	125.3	4.28	4.9
Composite	629.7	19.01	3.5

5. CONCLUSIONS

Epoxy resin with refractive index matching that of the glass fibers has been developed. A setup modifying the VARTM process has been developed to manufacture transparent FRP composites. Significant clouding can form if the mismatch is greater than 0.01. Optically transparent FRP composites have been manufactured using the vacuum infusion process. Density, fiber volume fraction, tension and flexure tests have been conducted to evaluate the performance of new materials. Results show that the manufactured panels are of good quality and exhibited good mechanical properties. These new transparent composites will find applications in windshields, windows and other components where a strong, lightweight transparent material is desirable

6. ACKNOWLEDGMENTS

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