Session 2663

Introduction to Low-Cost Manufacturing of Polymeric Composites

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Abstract
Composites are popular in high performance applications owing to their high specific strength characteristic and an endurance limit greater than that of traditional structural materials such as steel and aluminum. The paper discusses an experiment designed for students to be exposed to the low-cost manufacturing of high performance composites. The experiment is designed for a junior level manufacturing processes laboratory.

In this experiment, students use the Vacuum Assisted Resin Infusion Molding process (VARIM) to fabricate woven polymeric composite panels. A mold is loaded with the preform made of the reinforcement material. The mold is then closed and resin is injected into it, aided by a vacuum pressure at the vents to remove all the entrapped air in the preform and speed up the process. Resin flows in the plane as well as in the transverse direction of the preform.

Students evaluate the quality of their work by testing tensile coupons cut out of those panels. Four groups of up to five students work on producing four panels. Twenty tensile coupons are cut from each panel, and coupon tests enable students to compare spatial variation of properties within a given panel caused by the manufacturing process. In addition to the experience in processing, measuring, and statistical analysis, students become aware of cost considerations in manufacturing, since they are required to track materials and labor costs during the experiment.

I. Introduction

The VARIM process is popular because of its time saving and cost effective characteristics[1,2]. It is now used in many defense sector applications, in marine applications for building the outer bodies of ships and in the transport industry for the storage of materials. Much research has gone into fine-tuning the VARIM process[3,4] to get consistent mechanical properties. The present experiment aims to expose undergraduate mechanical engineering students to the manufacturing and related technologies of non-traditional polymeric products. The experiment is conducted over three lab meetings – two devoted to fabrication and one to the testing of tensile coupons cut out of the panels. Figure 1 shows a typical VARIM setup and Figure 2 shows a schematic of this process.

Figure 1 VARIM fabrication setup photograph

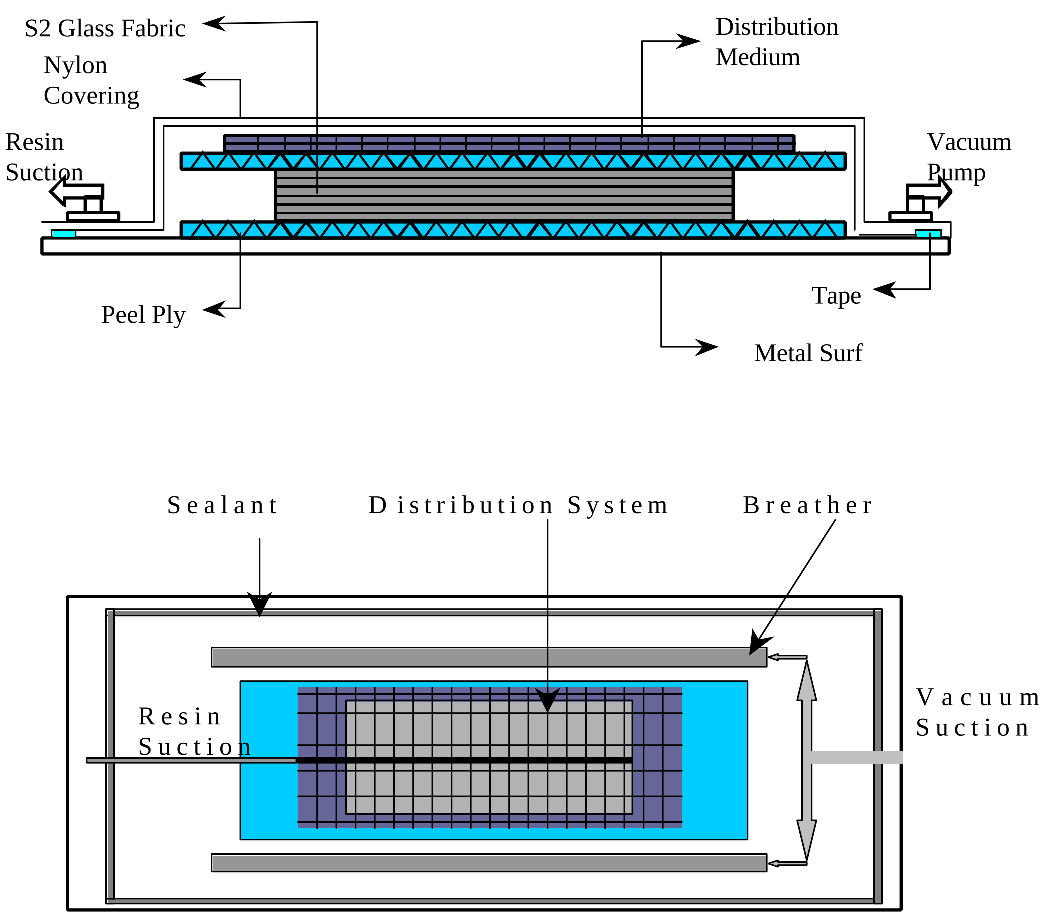

Figure 2 VARIM fabrication schematic

II. Session 1 – Preform and mold preparation

Surface preparation: Panel fabrication is done on a metal sheet. The surface is first cleaned with acetone to remove all the dirt. Two layers of mold release agent (Frekote-700 NC) are applied to the metal surface to facilitate the easy removal of the panel after fabrication.

Sealant: A sealant is applied on the metal surface so that it forms an approximate square shape. The sealant seals off the vacuum bag and help to maintain a uniform vacuum throughout the experiment.

Peel ply: This is a porous release material which facilitates the resin to flow through and leaves an impression on the part suitable for secondary bonding without further surface preparation.

Fabric layup: The fabric used for the present process is S2 glass fiber with 933 sizing. The panel size is 2 ft. $\times$ 2 ft. An extra 1 in. of fabric is cut on each side to allow for trimming after fabrication. The fabric is cut to the required dimensions and then 8 layers of plain weave fabric are stacked up to generate panels of approximately 0.1 in. thickness. The fill and the warp fibers should be perpendicular to each other and parallel to the corresponding fill and warp fibers of the other plies.

Breather: The breather material acts as a distributor medium for the air and escaping volatiles and gases. It also acts as a buffer between the bag wrinkles and part surface. It is a highly porous material and mostly made of fiberglass, polyester felt and cotton.

Vacuum gauge: A vacuum gauge is attached to the pipe that comes from the vacuum pump to the vacuum bagging. This always helps to keep track of how much vacuum is being maintained in the vacuum bag. The maximum vacuum available is about 29 inches of mercury. The gauge also helps detect any leaks in the bagging or in the arrangement.

Distribution medium: The distribution medium is laid on top of the peel ply that comes over the top surface of the fabric layers. This helps to maintain an even distribution of resin on the top of the panel and facilitate the flow of resin through the thickness of the panel.

III Session 2 – Resin injection and curing

Preparing the mold for resin injection requires the mold to be evacuated for at least 12 hours prior to resin injection. Bag leaks are often the most common problems observed during the fabrication process. This may be due to the damage of the nylon film before cure. Nylon film is hygroscopic and subjected to moisture changes due to changes in the moisture level in the surrounding environment. Dry and brittle film can cause cracking when it is handled too much. There is also a possibility of leaks being at the nylon material and sealant interface. Once the leaks have been removed and the vacuum bag completely sealed, the vacuum pump is kept running for at least 12 hours to achieve a good vacuum in the bag. Pleating is an important step involved in the fabrication of the panel. The pleats help avoid air pockets in the panel. The pleats go along the edges of the fabric lay-up. The pleats help the mold direct the air entering the mold through any of the leaks, to go through it and then subsequently through the vacuum line. The air entering the pleats does not enter the panel directly and helps to maintain a good vacuum in the fabric lay-up.

Next, the resin is injected into the mold. Before adding the resin to the mold, it has to be free of all the air pockets that may cause voids if they enter the mold. For this purpose, the resin is mixed with the hardener in a proportion of 100:30 by weight and kept in a cylinder that maintains a vacuum. This enables the suction of all the air pockets that have been trapped in the resin. Once the resin is ready, it is injected into the mold at a very slow rate. The flow of resin is controlled in such a way that it is allowed to flow in the distribution medium for some distance and then the resin inlet is shut off to enable the resin to go through the thickness. This cycle is repeated until the whole panel is soaked in resin. The vacuum pump is kept running for the next 24 hours when the resin undergoes a room temperature curing cycle. Time constraints prevent the students from performing some of the tasks in the fabrication process, and the parts they don't do are done by a lab assistant before or after class. The complete cure cycle (Figure 3) was developed with the data sheet provided by the manufacturer of the resin. After curing and before class, the panel is removed and coupons cut as described in the next section. Strain gauges are mounted to the coupons by the lab assistant.

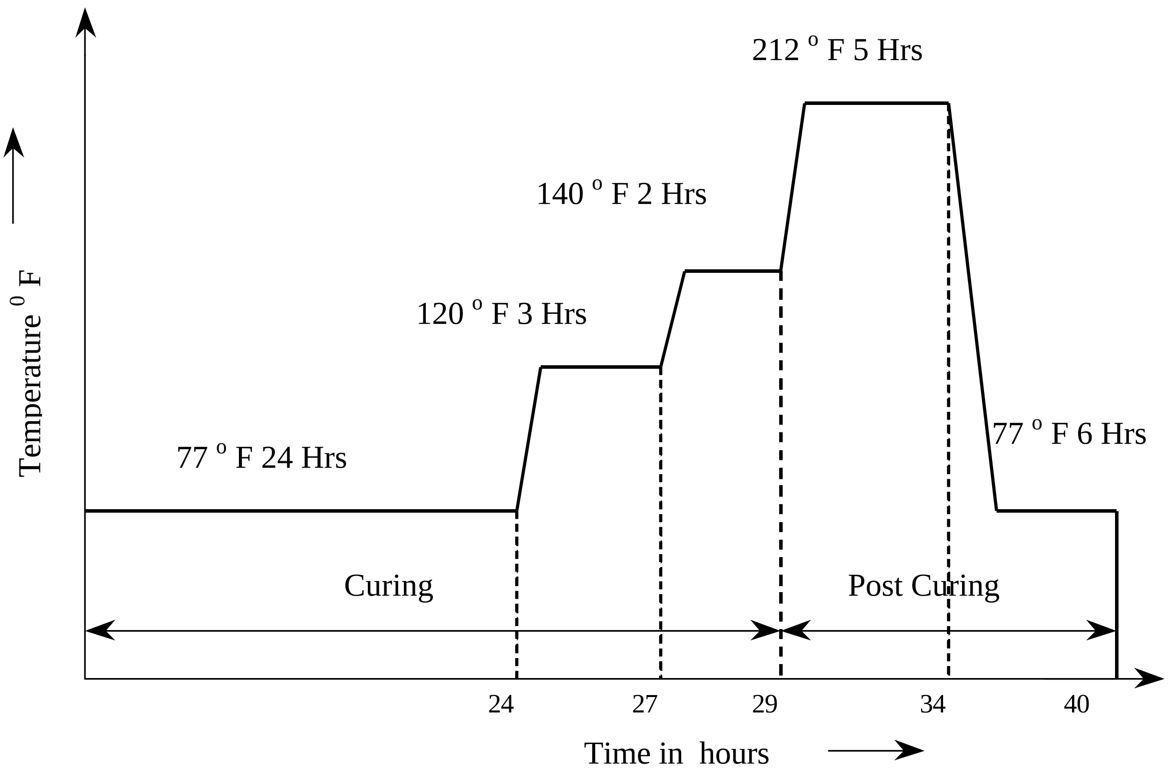

Figure 3 Cure cycle for S2 glass fiber / SC-15 epoxy resin panel

IV Session 3 – Tensile coupon testing

The fundamental material properties ultimate tensile strength σ_{ult}, and initial Young's modulus E are obtained using the tensile testing method. Samples are cut from the panels with dimensions per the standard ASTM 3039[5]. The test specimen (Figure 4) has a constant width and the axial load is transferred to the specimen via the grip shear force. To avoid failure near the grip or in the grip, tabs are provided with end tapers. The taper helps the smooth transition of the stress from the grip to the middle section of the specimen. This method is suitable for specimens up to 0.55" thick.

All tests are performed on MTS testing machine with an Instron Controller 8500 series. It has a hydraulic grip with 67.5 kip capacity and the testing machine has a capacity of 110 kips. The arrangement of this testing machine is shown in Figure 5.

The tension tests are performed with clip gauge extensometers as the displacement measurement units. The clip extensometer has a gauge length of 1 in. The loading rate used for the tension tests is 125 lb/sec and the data is acquired at a rate of 100 points per second. The ultimate tensile strength, Young's modulus and Poisson's ratio of the composite sample is measured. Typical results are shown in Table 1. Figure 6 shows the stress-strain curve. The Young's modulus is the slope of the straight part of the curve, which is the elastic region. Figure 7 shows the composite coupons that failed in a tension test. The characteristic brooming effect is seen during the failure of a composite specimen. Students are required to compile data showing spatial variation of properties within a panel as well as variability between processes, giving them a good feel for process variability. They are also required to track material and processing costs based on assumed fabric cost per unit area, resin per unit weight, and an assumed labor cost per unit time. The assumed cost basis is given to the students in Table 2.

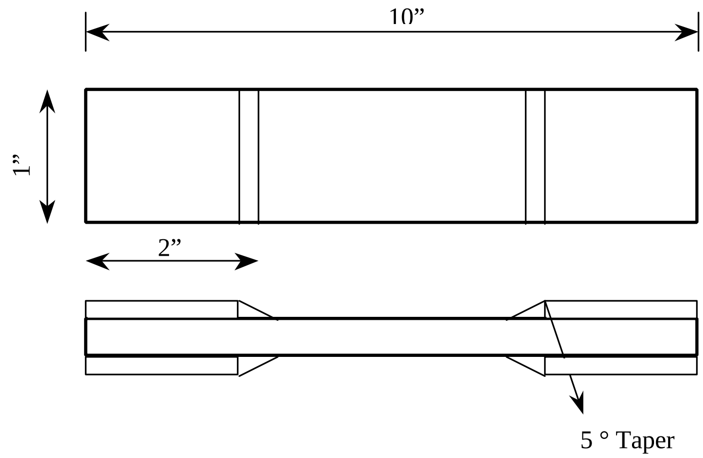

Figure 4 Standard tensile test specimen

Figure 5 Tension test setup

Table 1 Static tensile test results for S2 glass plain weave/SC-15 epoxy resin composite

Properties	Symbol	Unit	Value
Young's modulus	E_x/E_y	GPa	29.69
Ultimate tensile strength	σ_{ult}	MPa	522.20

Table 2 Composite coupon fabrication and testing raw cost data

S2 Glass Fabric	
Cost of 50 in. wide, 208 yd long plain weave epoxy compatible roving	$1573
(supplier: Owen-Corning, PA)	
SC-15 Resin (Part A and Part B approximately 3:1 by weight)	
Cost of 45 lb Part A (resin) and 13.5 lb Part B (hardener)	$439
(supplier: Applied Poleramic, Inc, Benicia, CA)	
Technician	
Cost of skilled technician with all related overhead costs	$50 / hr
(based on tooling and instrumentation costs, utilities, wages and benefits)	
Student Worker	
Cost of student labor (no benefits)	$10 / hr

The students are required to calculate the costs of the entire test program and then translate that into a per coupon basis. The following guidelines are suggested to the students and they are required to outline their detailed procedure:

- Fabric cost of a panel is calculated based on the total fabric area used (inclusive of any fabric wasted during trimming)
- Resin cost is based on the weight of resin used with an assumed 10 % excess used (resin weight is obtained by subtracting fabric weight from panel weight)
- Student labor costs are based on number of students in the team, number of lab sessions and total hours of work per session
- Technician costs additionally include hours spent outside of class in time-consuming activities that cannot be completed during class (such as evacuation of resin-filled mold to remove all air bubbles, post-curing of the panel etc)
- Cost of the entire test program is calculated by adding costs for all student teams
- Cost per coupon is obtained by dividing the above costs by the number of coupons tested

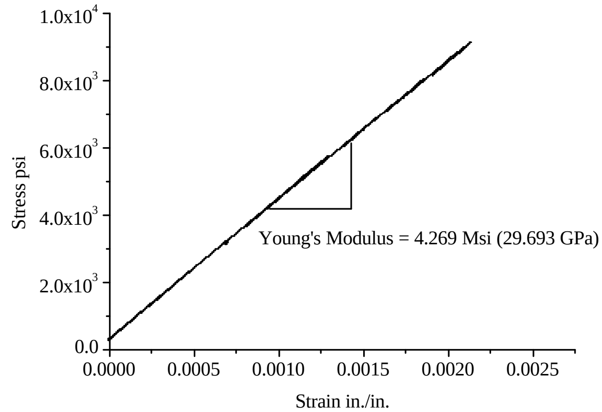

Figure 6 Stress-srain response for S2 glass/SC-15 epoxy resin coupons

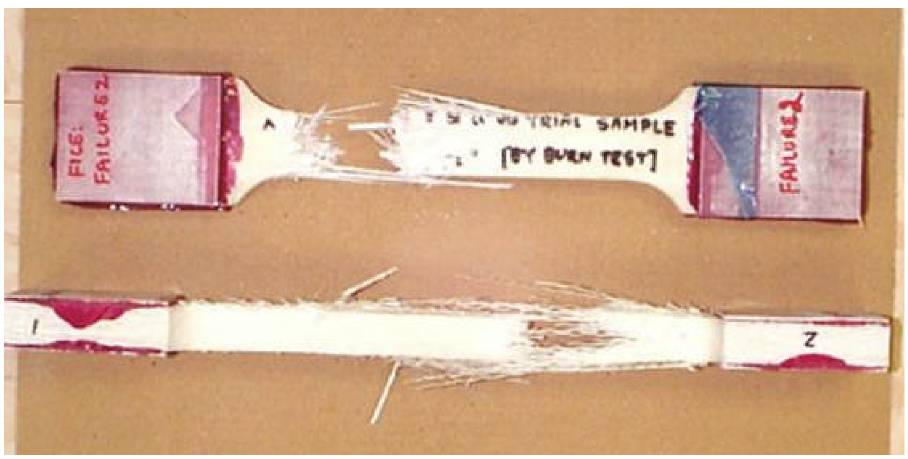

Figure 7 Composite coupons failed in tension test

V. Conclusions

Students gain a comprehensive hands-on exposure to a commercially popular manufacturing process for non-traditional materials – with exposure to manufacturing processes, sample preparation, testing, data analysis and cost calculations. This gives them a good feel for the technical and business aspects of the manufacture of non-traditional materials.

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