Replacing Glass Fiber and Carbon Fiber Products with the Thermoforming of Thermoplastics and Thermoplastic Composites to Reduce Costs and Increase Time Savings

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Abstract

In the rally racing industry, light pods are used during inclement weather and during night races. These pods provide more light output and are made from glass fiber or carbon fiber fabric.

This paper illustrates the cost and time savings achieved as well as the improvements in quality found by replacing the current method of production with the thermoforming of acrylonitrile butadiene styrene (ABS) sheet. The paper also explores the possibility of thermoforming thermoplastic composites, in this case, Tegris.

Introduction

Rally racing is a motorsport where highly modified cars race down dirt or tarmac roads at high speeds. The drivers and co-drivers must be able to navigate their way through twists and turns, through towns and forests, as quickly as possible. A single accident could cause irreparable damage to the car causing the team not to finish the stage. The teams race regardless of weather, time of day, or track conditions.

On occasion, the teams need more light for better visibility. To achieve this, the cars are fitted with light pods. Designs for these light pods vary greatly among number of lights, placement on vehicle, and overall appearance. The current method of production is to use glass fiber or carbon fiber fabric. The fabric is pre-impregnated with resin and laid-up manually on a mold. Gel-coat is also used to help with strength and visual appearance. The light pods are thick and heavy for strength and rigidity.

The thesis for this project is that it is more time and cost-effective to thermoform composite parts from thermoplastic sheet than to use the existing process. The four individual performance objectives are as follows: make a prototype; create two molds from the prototype; create a part from both molds; and create a duplicate set of molds.

The Current Method

Currently, most light pods are made by employees who place each sheet of pre-impregnated glass fiber or carbon fiber fabric onto a mold. Depending on the company, the glass/carbon fiber fabric may be stippled with resin instead of using pre-impregnated fabric. The mold is covered with a bag and the layers of resin-impregnated fabric are pressed together. The vacuum-bagged composite will then be transferred to an oven to cure. Curing takes several hours though process times vary on size and thickness of part. Once cured, the mold is taken out of the bag and the part is separated from the mold. After separation, final trimming may be required. The part may then be painted or left as-is depending on visual preference.

The Thermoforming Process

There are several different types of thermoforming processes. The process used for this project was single stage drape-forming using the Pennsylvania College of Technology Plastics Innovation and Resource Center (PIRC) MAAC thermoforming machine. A sheet of plastic is placed in the clamp frames. The clamps close, holding the plastic in place, and the carriage shuttles into the oven where the material is heated to processing temperature. This could be designated by either a timer or an infrared thermometer built into the machine; for this project the timer was used.. Once time or temperature is reached, the carriage shuttles out of the oven and hovers over the mold. The mold rises into the plastic sheet so the vacuum box top surface contacts the sheet. The vacuum is activated and draws the plastic sheet to the contour of the mold, whether it is a male or female mold; for this project two male molds were created. The vacuum is held while cooling fans allow the plastic to solidify. Once the cooling cycle is finished, the vacuum is deactivated and the machine pressurizes the vacuum box, assisting with part ejection. At the same, time the mold is lowered. Once the platen reaches its lower limit, the clamp frames open and the part is removed. From here, the part requires additional trimming of excess material. This process can take as little as two minutes to more than ten minutes depending on size, thickness, and type of material used and process used.

Materials

Woven glass fabric coupled with an epoxy resin is used to create a variety of parts. The glass fiber fabric adds greater strength than using just the resin while the resin allows the fabric to bond together in layers and allows the fabric to retain the shape of the finished part.

Woven carbon fiber fabric coupled with an epoxy resin is used to create the same variety of parts as glass fabric. Carbon fiber is lighter and stronger than glass fiber but is also more expensive. The resin used for carbon fiber is usually clear to allow the finished products to show off the carbon fiber weave for visual appearance.

ABS is a thermoplastic that is used for a large variety of products from suitcases to vehicle bumpers. Unfilled ABS sheet has a lower density than carbon/epoxy or glass/epoxy composite materials. Material costs are also much lower. For this project, 1/8" (3.18mm) thick ABS sheet was used.

Tegris is a thermoplastic composite made of one hundred percent polypropylene. It consists of a polypropylene ribbon woven fabric impregnated with a polypropylene resin. This material is used to make high strength composite parts similar to carbon/epoxy composites but has the added benefits of higher strength-to-weight and it has the ability to be reheated and remolded.

Designing the Part

The lighting component of choice was measured. The lights chosen, Hella 500FFs, are 7" (177.8mm) in diameter and 2.5" (63.5mm) thick. Using SolidWorks, a general shape was created with enough offset to allow the lights to be mounted to the light pod without interference. From the front view the rest of the light pod design was created and designed to keep the part smaller and physically appealing. From these two designs, a three-dimensional model was created to ensure physical appearance satisfaction.

Prototype

A prototype was made using a combination of high-density construction foam, low-density expandable foam, automotive body filler, and some glass fiber impregnated with polyester resin. The glass reinforcement was laid-up on the vehicle hood of choice to establish the contour of the hood. The front profile of the part design was printed out and attached to a thick sheet of poster board and cut-out. The poster board was placed on high-density foam sheets glued together with Gorilla glue and then was sanded smooth. The foam was glued to the glass fabric on the hood and expandable foam was sprayed underneath to fill in the voids. The foam was covered in a layer of body filler and sanded to a smooth finish. One layer of glass fabric was laid-up over the prototype and the hood using polyester resin. Once cured, the prototype and glass fiber part were removed from the hood and separated from one another. The glass fiber part was trimmed and the front half was separated from the rear half due to mandatory overhang. The prototype part was created from just one layer of glass fabric whereas typically they require at least three layers to be structurally rigid.

Mold Making

Depending on the company, mold making for all four materials mentioned could use the same process. The molds could be cast aluminum or machined from a block of aluminum. For thermoforming, the aluminum mold would be placed on top of a box made from wood, steel, or a number of other types of materials. The mold would also need vacuum holes drilled into it to allow the machine to draw a vacuum between the mold and the plastic sheet to form the part.

If the company doesn't have the budget for more expensive molds, or only small production runs are required, the molds could be made from less expensive materials. For this project, the vacuum boxes were made with ¾" (19.05mm) thick birch plywood. Birch was used because the pores of the wood are smaller than other woods which helps keep the box airtight. The plywood was cut to size and then screwed and nailed together. Since the boxes were quite large, reinforcement baffles were installed inside the box with portions of the baffle cut out so the entire box could still draw vacuum. This box was then covered in a layer of luan sheet. The luan skin rises above the plywood vacuum box roughly ¼" (6.35mm) which helps keep the mold air tight when the mold is pushed into the pliable plastic sheet. The luan was attached with nails and the entire box was covered in duct tape, with the exception of the top surface of the mold. The duct tape ensures the box stays air tight throughout the molding process. Using a hole-saw, a hole was cut in the center of the bottom of the box for vacuum line fitting.

The front half of the prototype mold was waxed and set inside of a box and Repro slow-cast urethane was poured around the prototype mold to produce a female mold. Repro is a two part rigid urethane cast used primarily to make thermoforming tooling. The mold was waxed and ½" (12.7mm) birch plywood, cut to the general contour of the mold and offset by roughly ¼" (6.35mm), was laid inside the female mold to fill up space and lower the overall cost of the mold. More Repro was poured into the mold and around the plywood to establish the finished front half of the mold. Once the finished male mold was removed from the female casting mold, the male mold was aligned on the vacuum box top surface. The mold was traced to the top surface and the mold was removed. A layer of automotive body filler was placed along the traced contour. Before the body filler was allowed to cure, the male mold was placed back in position on the top surface and a fillet was established using a finger. Once the body filler cured, the mold and the fillet were sanded smooth, the vacuum box was bolted to metal c-channels to provide extra height. The top surface, including the mold, was then re-attached to the vacuum box. This mold is shallow, only 2" (50.8mm) deep, with little to no degrees of draft.

The rear half of the mold was cast from the glass/polyester prototype part. The vacuum box top surface was removed and the glass fiber part was set on top. Plywood was cut to the contour of the part and silicone caulking was used to seal the edges. Two holes were cut on each center light-housing to allow air to escape and to enable quick casting. Once the Repro was cured, the glass/polyester and wood were removed and the vacuum box top surface, including the newly-cast mold, was reattached to the vacuum box for forming. Unfortunately, due to time and budget restraints, only one set of molds was created.

Part Forming and Trimming

Both parts were formed using the same settings, with the exception of height. For both molds, the ABS plastic sheet was heated to 345°F (173.9 °C) for 145 seconds. The sheet was heated at a slower pace than what is typical for ABS due to the fact that the ABS sheet in stock had absorbed some moisture. The part was formed using 27" of mercury (1.01 bar) and cooled for 120 seconds using 8 psi (0.55 bar) of air pressure.

The first mold formed was for the front half of the part. After the part was removed from the machine a band saw was used to roughly cut out most of the surrounding plastic. A flush trim router bit was used to trim the rest of the excess plastic away from the part.

The second mold formed was for the rear half of the part. After the part was removed from the machine a band saw was again used to roughly cut out most of the surrounding plastic. A flush trim router bit was used to trim the rest of the excess plastic away from the part and a band saw was used to cut the contour of the flange. The two halves of the part were joined using bolts, plastic epoxy, and an airless plastic welder.

Installation

Once the trimming was completed each light had to be drilled in three places and rivets were used to hold custom-made brackets 120 degrees apart to the light housing. Each light was attached to the light pod using bolts, nuts, and springs for easier aiming of the lights.

The pod was placed on the hood and four holes were drilled through both the light pod and the hood of the vehicle - one behind each of the center light housings and one along each outer light-housing. Clevis pins were used to hold the light pod to the hood for quick and easy installation and removal. Due to the weight of the lights and the loss of structural integrity caused by cutting the holes for the lights, the light pod was shaky. A bracket was made using 3/16" (4.76mm) thick metal stock. This bracket was bolted to the front of the light pod and attached to the hood with a clevis pin. All four lights were wired in compliance with the manufacturer's instructions and quick disconnects were used between the light wiring and the wiring leading up to the lights. The quick disconnects allow for quick and easy installation and removal of the light pod.

Forming Tegris

Tegris parts are currently made using the compression molding process. Compression molding is similar to thermoforming, however the sheet is placed into a two piece matched metal mold, similar to an injection mold, and the mold is heating to processing temperature. The mold is clamped together under high pressure and then cooled while still held under pressure. When compression molding Tegris, the mold is heated to 250°F (121.1 °C) and the mold is clamped using 300 psi of pressure.

Two attempts were made to therrmoform the Tegris sheet. A shallow mold was selected so no issues of deep draw would be present. The sheet was cut and placed in the clamp frame. For the first attempt the sheet was heated to 350°F (176°C). Once the clamp frame shuttled out of the oven it was evident that the Tegris had shrank enough that the sheet pulled out of portions of the clamp frame. Since the material shrank out of the clamp frame, the sheet was not capable of holding a vacuum seal across the mold so forming was impossible. For the second attempt, the sheet was heated to 450°F (232°C) to study the effects of heating the material. At 405°F (207.2 °C) the machine was stopped because the material shrank out of the clamp frame. After looking at the forming data for compression molding Tegris, it was decided to place a sample of Tegris in a drying oven until the material reached 260°F (126.7 °C). Once it reached the desired temperature, the material was removed and checked for pliability. At this temperature it was decided that the material was not pliable enough to thermoform with the machine at hand without risk of damage.

Izod Impact Testing

An Izod impact test was conducted on three of the four materials: glass fabric/polyester, ABS and Tegris. Unfortunately carbon fabric/epoxy could not be obtained for testing. The samples were all 2.5" x 0.5" x 1/8" (63.5mm x 12.7mm x 3.18mm). The glass fiber and ABS were both impacted with a 5 ft/lb (6.78 N/m) hammer and the data was collected. Tegris required a 30ft/lb hammer due to its strength. All the data collected is displayed in Figure 1. The figure illustrates the strongest material tested was the Tegris thermoplastic composite. This is due mainly to the sample bending and twisting underneath the impact surface of the hammer. Also note that the ABS has almost as high of impact strength as the glass fiber composite.

Figure 1

Run	ftlb/in	Nature of break
Acrylonitrile Butadiene Styrene (ABS)		
run 1	3.437	Complete Break
run 2	5.015	Hinge
run 3	3.711	Complete Break
average	**4.054**	
Glass Fiber		
run 1	4.543	Complete Break
run 2	5.348	Complete Break
run 3	5.372	Hinge
average	**5.088**	
Tegris Thermoplastic Composite		
run 1	13.469	Non-break
run 2	16.179	Non-break
run 3	12.278	Non-break
average	**13.975**	

Time and Cost Comparison

Low cost materials from Wal-Mart were used to make the glass fiber prototype. The costs of this one-layer prototype part were $30 in glass fiber mat and roughly $10 in polyester resin. Again, at least three layers are required to make this part structurally sound and cost about $100 in materials. It took 4 hours between preparation, laying up the glass fiber, and waiting for the resin to cure.

It would take two full sheets of general purpose ABS at a price of $50 per 4' x 8' (1.2m x 2.4m) sheet to yield 3 complete parts which equals about $33 per part. It took 10 total minutes to make both pieces of the part and another 20 minutes for post-processing trimming and joining the two halves together.

At a wage of $10 per hour it would cost a total of $38 per part including labor to thermoform the part from ABS. At the same wage it would cost a total of $140 per part including labor to make one part from glass fiber/polyester. **This results in significant time and cost savings by thermoforming these parts compared to using glass fiber.** If a thicker sheet of ABS was used, the mandatory overhang could be eliminated and the part could be made in one piece. This would lead to greater cost savings since only one mold and one vacuum box would need to be made. This would also require one sheet slightly larger than one of the two sheets used in this project and would also lead to 5 minutes per part rather than 10. This would also save money by eliminating post processing joining of both halves since they were molded together.

Improvements

There are a few quality issues with glass fiber layup. One issue to watch out for is delaminating. If an air pocket exists in the part, overtime it could grow and separate the layers of the glass fiber part, resulting in a weak spot.

One improvement that thermoplastics have over glass fiber and carbon fiber thermoset composites is the ease of repair. If glass fiber gets cracked it requires a lot of work to repair. First, the end of the crack needs to be drilled through so the crack does not continue to grow. Then a bore is drilled along the entire crack. This allows dry glass fibers to be added to the crack without increasing the thickness of the part. Once these fibers are laid inside the channel, resin is stippled onto the dry glass fiber strands and the excess is sanded off. To repair a crack in a thermoplastic, the crack could be plastic-welded by either a hot air plastic welder or an airless plastic welder. A hot air plastic welder heats a rod of plastic, the same material as the part, with a hot jet of air and the plastic bonds the part back together. An airless plastic welder is essentially a soldering iron with a flat tip. The iron heats up the plastic and bonds the two sides together. A plastic filler rod could be used to provide more material if needed but is not necessary. An airless plastic welder does not provide a uniform weld whereas the hot air plastic welder does. The excess material could then be sanded smooth.

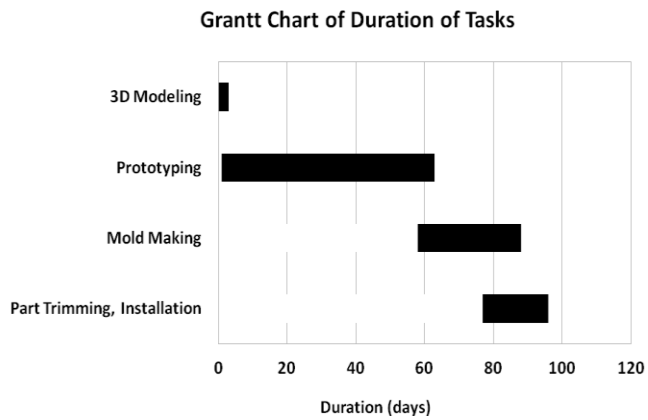
An improvement of thermoforming over thermoset composite layup is the result of experimentation with different materials. Traditional composites have a limited number of materials that can be used for this process, whereas thermoforming allows for a wide range of materials that can be used. To prove this point, one part was made from 1/8" (3.18mm) thick ABS and one part was made from the front piece mold out of Kydex. The Kydex sheet was ¼" (6.35mm) thick and is a combination of ABS and polyvinyl chloride, or PVC. The part formed well and was ejected early to reduce the chance of the part sticking to the mold since the mold had little draft. A part would have been made from the second mold however the sheet in stock was a little smaller than what was needed.

A third improvement occurs in using a thermoplastic rather than the glass fiber or carbon fiber composite. Glass fiber and carbon fiber polyester or epoxy can only be molded once and can only be used on the vehicles the parts were made for without extra modification. Some parts may be modified to fit other vehicles by either cutting pieces away or adding more glass/carbon fiber to essentially make the part fit. Since thermoplastics are capable of being reheated and reshaped it is possible to take a model-specific part and with the use of a heat gun reshape the part to conform to the vehicle. This means that almost every part could be declared universal.

Breakdown of Time

This project began on January 22nd, 2013 and was completed on April 21st, 2013, lasting a total of 90 days. Designing took 3 days, prototyping took 62 days. It took 30 days to make both molds and form parts and 19 days were spent trimming and installing the parts. Some of these phases were done during the same time frame as illustrated by Figure 2.

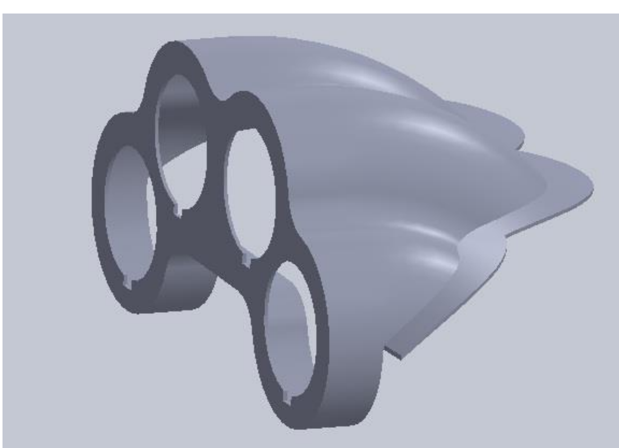
Figure 2



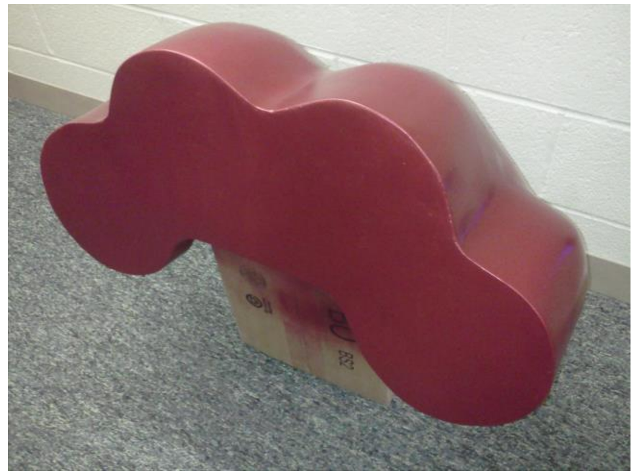
Conclusions

According to all the data collected and analyzed it can be determined that there is adequate evidence to illustrate the theory that replacing composite products with thermoformed equivalents is not only cost effective, but time effective. Quality of the parts increase and repair is also quick and easy. It is also plausible that Tegris thermoplastic composite is not thermoformable without the use of a machine capable of forming at high pressures.

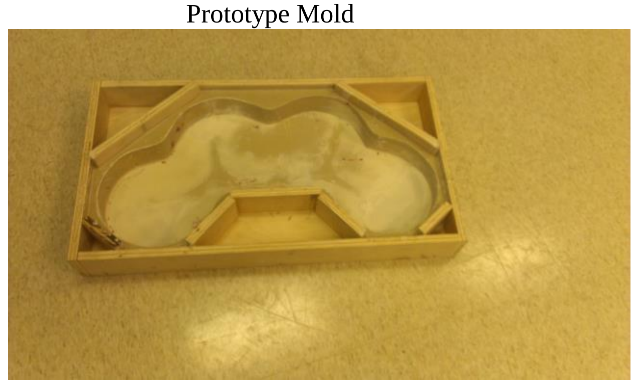
Appendix



Three-Dimensional Model Design

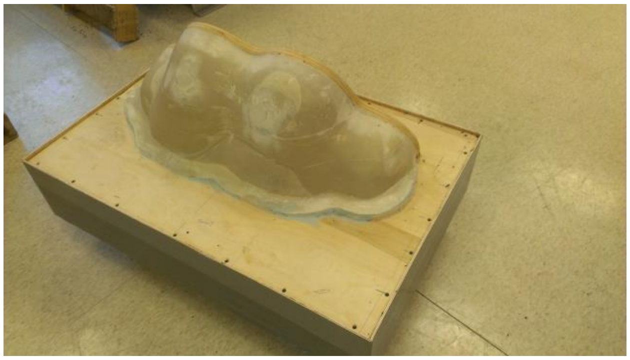


Prototype Mold



Front Mold Casting Cavity

Front Mold Complete



Rear Mold Complete

Finished Product Installed on Vehicle

References

1. Fan, Z., White, C. B., Zhu, L., Zhang, Y., & Chen, Y. (2007). Jounal of Thermoplastic Composite Materials. *Estimation of the Molding Thickness of Knitted Fabric Reinforced Thermoplastic Composites Produced by Hot-pressing* .

2. Hone, M. (2012). Gizmag. *Tegris: Thermoplastic Composite Takes on Carbon Fiber* , 1.

3. Jacobs, J. A.-8. (2011). Composites for Automotive, Truck and Mass Transit.

4. Jacobs, J. A.-8.-8. (2010). Method for Forming a Thermoplastic Composite.

5. Makin, S. P. (2011). *Method of Making Automotive Body Parts* .

6. McCool, R., Murphy, A., Wilson, R., Jiang, Z., & Price, M. (2011). *Thermoforming of Continuous Fibre Reinforced Thermoplastic Composites* .

7. Sandler, M. (2010). *Rally Car Dudes* .

8. Suresh, S., & Zhu, K. (2011). Applied Mechanics and Materials. *An Overview of Recent Research Works on the Forming of Thermoplastic Composite Sheets* .

9. Wang, P., Hamila, N., & Boisse, P. (2012). Intraply Shearing Characterization of Thermoplastic Composite Materials in Thermoforming Processes.

10. Zuehlke, J. (2009). Motor Mania. *Rally Cars* .