APPLICATION OF COMPOSITE MATERIALS IN SOLAR CARS AND TECHNIQUES FOR ITS PERFORMANCE IMPROVEMENTS

by

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When I first set out to focus on the advancements of composite for this thesis, I knew it would not be easy. Having chosen this topic due to the experience I had with composite throughout the years was the exact reason I knew I would not succeed the first time. I knew it would take trial after trial to fine tune this new method, in this case, vacuum bagging. Although I was not able to fine tune the process for this thesis, I did take one trial and error out of the multiple that I know are to come for others. I gained knowledge that will be passed on to other students through means of a shared data base.

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Abstract

The focus of this paper is on the polymer matrix composite dashboard of a solar car, Racing on Solar Energy (R.O.S.E), made of carbon fiber with Bondo's high strength polyester Fiberglass Resin. While a composite piece was pulled from a custom-built composite tool made of fiber glass and fiberglass resin via a plug and mold method using a wet layup, the resulting piece was not of good surface quality. Meaning that there were many voids, and the decision was made to cover the piece with a carbon fiber vinyl as opposed to leaving the surface as was. The goal of this paper is to not only highlight the history of composite material along with the important role they contribute to renewable energy, specifically solar cars, but to outline another method of laying up carbon fiber via vacuum bagging to produce a more satisfactory composite piece. While the vacuum bagging was unsuccessful, the process and materials used were correct and can be evaluated as to how to improve the outcome for another attempt. Methods used are methods professional composite companies use, but I and not a certified composites technician and have only learned through resources online, speaking to professionals, and trial and error.

CONTENTS

INTRODUCTION

Broadly speaking, composites are two or more chemically or physically distinct materials when combined, have improved properties as compared to the individual components (Umair Bukhari 2013). Composite materials are classified into two groups of natural and synthetic composite materials both of which are consisted of a matrix phase and a reinforcement phase. For example, wood is a natural composite made of lignin that binds to cellulose fibers and hardens and strengthens the cell walls of plants. Adobe bricks form composites aswell, the combination of mud and straw is stronger than either the mud or straw individually. Synthetic composites use human made material to reproduce this natural method. Synthetic composites are classified into three main groups: metals matrix composite (MMC), ceramics matrix composites (CMC), polymers matrix composites (PMC) and fiber reinforced plastics (FRP).

MMCs consist of metals or alloys, such as aluminum or magnesium, that incorporate particles, whickers, fibers, or hollow micro balloons made of either metal as well or another material such as ceramics or an organic compound (Macke et al., 2012). Applications of MMCs are seen in industries such as aerospace, automotive and the energy sector for their higher modulus of elasticity and ductility. They, however, are heavier and more difficult to manufacture. CMCs use silicon carbide, silicon nitride and aluminum oxide and mullite as a matrix and the fiber material commonly used is carbon and aluminum oxide (Youssefi, n.d.). These composites materials are most desired in cases where resistance to high temperature and corrosive environment is considered necessary such as automobile engines, deep sea mining cutting tools as well as aircraft exterior. Lastly, and the focus of this paper, are PMCs and FRPs which are commonly referred to as reinforced plastics. Reinforced plastics comprise of a resin matrix consisting of either thermoset or thermoplastic and the fiber, which can be continuous or chop and can be synthetic or natural. The matrix is distinguished between thermosets and thermoplastic, in particular thermoset resin are classified as epoxy and polyester. The fibers we are most concerned with are the synthetic inorganic ones such as glass and carbon.

Composite laminates are usually composed of plies with different directions, where each ply is made up of unidirectional continuous fibers held together by a polymer matrix (Jefferson et al., 2018). Different methods of laminating are wet layup, also know as hand layup, and vacuum bagging, also known as vacuum bag laminating and resin infusion, more on these later.

Objective

The objective here is to highlight the unique ways composite materials are being applied in solar cars and to showcase real world applications at the college level. Projects such as those I will be mentioning in this paper contribute to a solar community around the world, where teams may be at different levels of experience but have a commonality towards a more sustainable future through innovative transportation technology. I will be comparing the different methods and pieces produced by both a wet layup and vacuum bagging while citing the necessity and benefits of vacuum bagging over the former. The importance of highlighting the history of composite material and applications is to provide a holistic understanding of how important they are as we move to more lightweight and efficient vehicles and components. The key is not only in how much composite material have developed over the years but also in how they have been adapted in all circumstances. Finally, my personal experience through which how I came to learn about composite materials is key in why I am choosing to further advance our techniques. The story of Team Sunergy, Appalachian State University's solar car team is crucial in providing a hands-on learning experience that make this learning and advancing possible. The same tool as well as the same resin and fiber are used to produce the composite piece. I am aware that the chosen resin is not meant for carbon fiber, meaning the high level of strength of carbon fiber is not fully taken advantage with this particular resin, however, to reduce the introduction of new variables in reproducing this process with a different laying up method, using the same resin was a necessity.

BACKGROUND

Composites date back to the ancient times during the Mesopotamia period around 3400 B.C. The Mesopotamians glued strips of wood at different angles to construct plywood. By combining mud/straw and wood/clay they built their homes. This was a common practice for civilizations around the world to use materials in their surrounding environment to fabricate their homes, and still is today. In 1200 AD the Mongols applied this method of composites to construct one of the most advanced weapons of its time. Made from a combination of bamboo, silk, cattle tendon and horns, and pine resin the Mongolian bow became a deadly weapon on the battlefield ("Mongolian Archery: from the Stone Age to Naadam", 2020). During the 1870s-1890s the first synthetic resins were developed, resins go from a liquid state to a solid state using a process called polymerization ("History of composites", 2021).

The biggest advancements of composite materials was from the emergence of a new era of plastics. In 1907 Leo Baekeland, a Belgian born New York chemist, discovered Polyoxybenzylmethylenglycolanhydride, also known as Bakelite ("Leo Hendrik Baekeland", 2017). These now prized collector items decorated the American home in the first half of the 20th century with bright and colorful toys, jewelry, billiard balls, telephones, and radios. By means of this chemical advancement we also saw the development of vinyl, polystyrene, phenolic, and polyester plastics. These synthetic materials outperformed their naturally derived resin in nearly every category, from strength, durability, versatility to heat resistance, and resilience to environmental factors. While these plastics provided several improvements, they alone could not provide the strength and rigidity needed for structural applications. These resins needed some form of reinforcement. In 1935, Owens Corning developed the first glass fiber reinforcement known as fiberglass and from here the Fiber Reinforced Polymers industry was born.

World War II necessitated composite materials to go from experiment to application. Applied for their high strengths and low weight properties, fiberglass reinforced polymers were also found to be transparent to radio waves. Radomes, originally made from molded plywood, were soon made from fiberglass further fostering the development of fiberglass as a structural material (Wahab, 2009). After the war had ended the drive for further innovating this technology persisted and so did the desire to venture out into other markets. The boat industry was one of the first beneficiaries with the first commercial boat hull being introduced in 1946 (Johnson, 2018). Developers like Brandt Goldsworthy, referred to as the “grandfather of composites,” manufactured a new process called pultrusion, this method produces dependably strong fiberglass reinforced products (Johnson, 2018). Goldsworthy also manufactured the first fiberglass surfboard, revolutionizing the sport. In 1963, British scientist W. Watt, L. N. Phillips and W. Johnson introduced a new carbon fiber manufacturing process that produced a much stronger product than processes years before (“DragonPlate”, 2019). Then in 1965, Stephanie Kwolek discovered the exceptional strength and stiffness of polyamide molecules that lined up to form liquid crystalline polymer solutions. This discovery made way for Kwolek’s invention of industrial fibers, today is most recognizable as Kevlar, a heat resistant material that’s five times stronger than steel, but lighter than fiberglass ("Stephanie Kwolek - American Chemical Society", n.d.).

Entering the 1970’s, we see a boom in composite advancements as the industry matures and manufacturing methods become more cost effective. On this wave of new manufacturing methods also came vacuum bag molding, vacuum bagging and large-scale filament winding. In 1982, solar pioneers Hans Tholstrup and Larry Perkin, travel across Australia from the West to the East in a home built solar car with a fiberglass body and clear fiberglass windows. It was from this achievement and Tholstrups urge to explore the boundaries of solar powered cars that the World Solar Challenge was born. Entering the 1990s and early 2000’s composite materials are now being used in manufacturing and construction. It was not until advancements of carbon fiber and fabrication of yarns containing up to 95% carbon, that the vast potential of carbon fiber began to be understood (“DragonPlate”, 2019). The technological advances of composite due to their stellar strength-to-weight ratios and stiffness-to-weight ratios has made them the popular material of choice for engineers around the world. Steel is largely being replaced due to carbon fibers' advanced properties. Today, composites are constituted to be used in different sectors such as military, marine, automotive, construction and have ventured into medicine, transportation applications, and renewable energy.

Composite Materials

The composite industry can be classified into three major categories: consumer, industrial, or advanced composites ("Composites Industry Overview", 2022).

Consumer Composites

Consumer products will generally be identified as products with cosmetic finishes. The sports and recreation sector use composites in marine products, sports equipment such as bikes, athletic equipment, and pools. Residential applications of composites will be found in kitchens and baths. Art installations and any projects individuals may utilize composites will also fall under this category.

Industrial Composites

Industrial composites are the material of choice when corrosive material needs to be protected or installations that must withstand natural elements or perform in adverse environments are required. Within this industry, composites are applied for their corrosion resistance properties, in pipes and tanks, handrails and grating; equipment subjected to corrosion, chemical exposure, and extreme environments such as, fans, pumps, blowers, scrubbers, and cooling towers along with a variety of other applications ("Industrial - Discover Composites", 2022). The construction sector also applies the reinforcement properties of composites for support beams and other structural elements as well as use composites for electrical components and equipment. With the growing demand of renewable energy, the wind industry has been the most rapidly growing sector of composites. New emerging offshore wind farms are pushing the limits of composites to produce bigger towers and longer blades.

Advanced Composites

Advanced composites employ the highest performance resin with high strength fibers paired with innovative manufacturing methods to produce composites that constantly exceed all limits. Among the first applications of composites was during WWII and since its beginning there, has had a consistent growth. Today, military grade equipment such as missiles, drones, aircrafts, munition, vehicle applications and several other weapons are made from composite to produce these high performing equipment (Fink et al., 2001). The increasing space and research activities are currently boosting composites in aerospace, having a role in space and aeronautics industries.

The transportation sector encompasses airspace, automotive and heavy vehicles and is the leading user of composites ("Transportation - Discover Composites", n.d.). Whereas of late automotives are going from using composites for interior applications to more structural and performance demanding components. This growth in automotive composites is being driven by the demand for lighter cars as we move towards fuel efficient vehicles and electric cars. The solar car collegiate competitions, Bridgestone World Solar Challenge and the American Solar Challenge, host teams from around the world that have used composites since its first inception following Tholstrups and Perkins cross country exhibition. Today, competing teams around the world showcase and compete cars that are reflective of the advancements in composite material to design and build durable, strong, lightweight vehicles.

Market Value of Composite Materials

The global composites market size was estimated at USD 86.4 billion in 2020 and is expected to expand at a compound annual growth rate (CAGR) of 6.6% from 2021 to 2028 ("Composites Market Size”, 2021).

The increase for composites is primarily driven by the aerospace and automotive industry’s demand for lightweight high performing materials. The electrical industry is expected to provide steady support in the composite market. Compared to their plastic counterparts, composite materials are impervious to electrical arcing or tracking and face minimal impact for these common electrical equipment conditions ("Electrical Composite Materials", n.d.). The global aerospace composites market size is forecast to reach around $41 billion by 2025, after growing at a CAGR of 10.5% during 2020-2025. A new rising market with exceptional applications is the wind sector. As wind blades continue to push the boundaries of size and energy production, it too is expected to be a driving force in the composite industry.

Composite Material and Renewable energy

Composites' role in the renewable energy industry is one that is only coming into production as climate change continues to cause catastrophic damage to communities all around the world. We are forced to rethink our consumption of resources and our means of living. So, as electrification of our automotives takes to the forefront and renewable means of production capture our energy sector, now more than ever composites deliver the high performance and lightweight properties needed to tackle this transition. As we have seen, the wind industry is one that has dominated the use of composites from blade production to rotor, foundation, motor, and the tower of a wind turbine. On February 25, 2022, the US federal government announced the sale of a $4.37 billion lease of 6 offshore wind areas, more than 488,000 acres for the development of offshore wind (Newburger, 2022). With no other material with the redeemable qualities of composites such as corrosion resistant, high strength low weight properties capable of tackling these growing innovations, composites are at the forefront of this transition to cleaner energy.

Composite Material and Solar Cars

The American Solar Challenge (ASC) and the Bridgestone World Solar Challenge (BWSC) are competitions that demand innovative solutions to bringing solar cars mainstream. The BWSC is the biggest and most prestigious solar car event in the world. The international event started in 1987 and since then has been sending teams across the outback of Australia to travel the roughly 1900 miles from Darwin to Adelaide, spanning the whole continent's outback. The ASC is a multiday 1,500-2,000 miles cross country endurance rally that takes place in North America every other year. The Formula Sun Grand Prix (FSGP) is a track event that occurs every year and serves at a qualifier for the ASC. Both bring collegiate level solar teams from around the world compete in this challenge to show off how their solar car and onboard system handle real world driving conditions. The competitions do not overlap each other, in order to give teams the most opportunity to attend both.

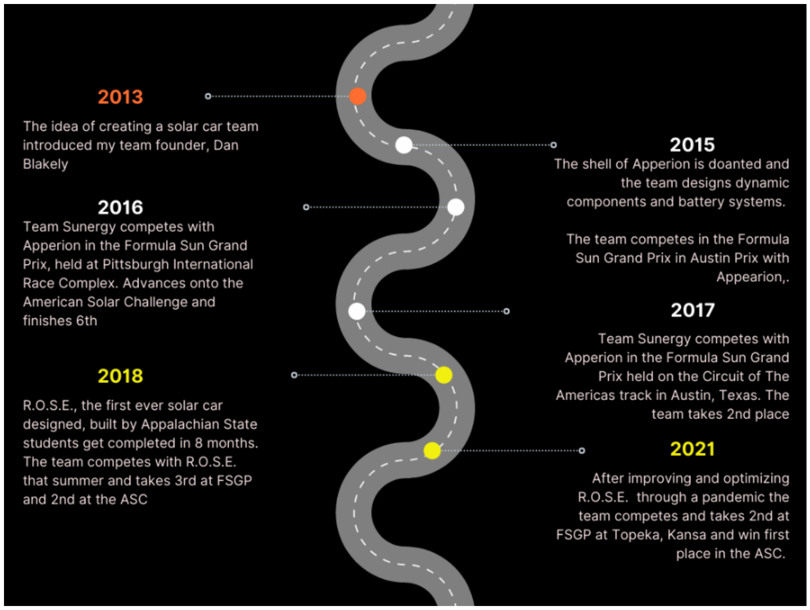
Solar cars in these competitions have used composites since the very first solar car was driven across Australia in 1987 with a fiberglass body and clear fiberglass windows. Since then, composites have pushed the limits of solar cars by meeting demands of lightweight bodies and composite pieces that have ultra-strength properties. Team Eindhoven has taken first place in the cruiser class for the past four races dominating the WSC. They are arguably the best solar car team in the world. All the vehicles in the Stella Family, including their Stella Vita, the Self-Sustaining House on Wheels, use carbon fiber for the body ("Stella Family — Solar Team Eindhoven", 2022). Agoria Solar Team, the Belgian team that took first place in the challenger class with "Bluepoint," in 2019 has a body that is made of TEI carbon Fiver, reinforced with Dupont Kevlar Fibers ("Agoria Solar Team | BluePoint", 2022). The Tokai Challenger, from Tokai University, and another powerhouse in the WSC, has a frame constructed from carbon fiber reinforced plastic (CFRP) (Kimura, 2019). University of Minnesota is one of the most decorated teams in America with a prestigious record of competitions and a total of 13 built vehicles. All of their vehicles are made from composite pieces and structures to not only add value to their interior but to serve as structural members of the car as well (("The Team — University of Minnesota Solar Vehicle Project", 2022).

Solar Cars at Appalachian State University

Team Sunergy, from the University of Appalachian in North Carolina, USA, is a unique team in the world of solar racing. While most of the teams come from engineering universities and or backgrounds, App comes from a liberal arts background (Stump, 2018). Meaning that while there may be a broad range of learning across the disciplines such as arts and science, there is no actual engineering program. However, the team does not believe this to be a disadvantage or render them less competitive. Rather than approaching the challenges set forth by the ASC and BWSC as engineering problems, they see those challenges as sustainability problems. In *Figure 1* a brief history of Team Sunergy is outlined. The conception of the team begins in 2013 from a group of students in an Electric Vehicles class. The founding member, Dan Blakely took the initiative to further learn about this solar community. It was at one of the conferences he attended that Iowa State donated the shell of one of their old cars and was later renamed Apperion. Apperion went on to be raced at multiple events mainly Formula Sun Grand Prix before it qualified for the first time for the American Solar Challenge in 2016. After another year at FSGP the team decided they are ready to enter the multi-occupant division of the competition known as the cruiser class. With the help of the team's composite company sponsor, VX Aerospace, the shell of the car was built. From design, build, and race the period was all in a matter of 8 months. In 2018 the team raced and tied for 2nd place at the ASC. After a long period of the warehouse being inaccessible due to COVID, the team was back to improving and optimizing systems in the car. During which the dash was created. With a team of new recruits and old recruits who had never been to a race, building an underdog nature around the team, Team Sunergy took 1st place for the first time in history.

Figure 1

Team Sunergy Timeline



R.O.S.E’s Dashboard Composite Tooling- Plug and Mold

In order to save weight in as many areas as possible, large components such as the shell are made of carbon fiber, with other supportive but not structural components such as door lips, tire cover tabs, and dash (*Figure 2*). In *Figure 3* we see the carbon fiber dash in two different stages of completion. The pink color areas are places where Bondo was used to fill the voids left from the wet layup method, and then sanded to a smooth surface (*Figure 3 (a)*). The surface was then prepared for the carbon fiber vinyl to properly adhere and can be seen fully covered on the right (*Figure 3 (b)*).

Figure 2

Composite parts of R.O.S.E.

Note: Picture of R.O.S.E pointing to all the carbon fiber parts in the car. From Willoughby, 2021. Photograph.

Figure 3

Dash in R.O.S.E.

(a) *(b)*

Note. Image (a) is the dash before carbon fiber vinyl, image (b) is after carbon fiber vinyl. From Garcia, 2021. Photograph.

Materials

Below, a complete list of all materials used in the process of making the composite tool, the plug, and molds, as well as the dash from a wet layup is presented.

- Blue foam board
- Foam Wire Cutter
- Loctite General Performance Spray Adhesive
- TotalFair Epoxy Fairing Compound (see *Figure 4*)
- TotalBoat 2-Part Epoxy Primer (see *Figure 5*)
- 3M Perfect-It Rubbing Compound, 06085, 1 qt

- 3M 05753 Perfect-It Wool Compounding Pad Double-Sided
- PARTALL Film #10 Polyvinyl Alcohol (PVA)
- Collinite 900 Mold Release Paste
- 20 Oz. Professional HVLP Gravity Feed Air Spray Gun
- TotalBoat Gel Coat
- Matte Fiberglass
- Fiberglass Resin (see *Figure 6*)
- Hexcel HexForce Carbon Fiber Fabric 2×2 Twill 3k 5.8oz/197gsm Style 284 with Primetex Finish (*Figure 7*)

FIGURE 4

TotalBoat TotalFairing Technical Sheet

WORKING PROPERTIES:	
Application Method:	Spreader, trowel
Application Temperature:	50-100°F
Working Time, 150g mass, minimum	15-20 minutes @ 90°F 30 minutes @ 70°F 45-60 minutes @ 50°F
Tack-Free Cure @70°F	1 hour @ 90°F 2 hours @ 70°F 4 hours @ 50°F
Time to Sand:	3 hours @ 80°F 6-8 hours @ 70°F 12 hours @ 50°F
Shelf Life:	1 year, minimum

PHYSICAL DATA:	
Components:	Two - Resin and Hardener
Vehicle Type:	Epoxy Resin
Resin Color:	Yellow
Hardener Color:	Blue
Mixed Color/Consistency:	Green paste
Mix Ratio (by Volume):	1A to 1B
Mix Ratio (by Weight):	100 A to 90B
Sag Resistance (Mixed):	>1" (Vertical Surface Test)
Weight (lbs/gal):	11
Resin Density (lbs/gal):	7.0
Hardener Density (lbs/gal):	6.4

Note: The technical data sheet is referenced for the worktime before the fairing hardens as well as the cure time before being free to sand. From "TotalFair Epoxy Fairing Compound", 2018 (https://www.totalboat.com/product/totalfair/).

Figure 5

TotalBoat 2-Part Surfacing Primer Data Sheet

APPLICATION DATA:	
Application Method:	Brush, Roll, or Spray
Number of Coats:	1-3
Film Thickness (per Coat):	3-4 mils wet
Pot Life:	8 hours @ 72ºF
Application Temperature:	45-125ºF
Recommended Finish:	Urethanes
Induction Time:	Induct for 30 minutes before reducing or application
Dry Time to Recoat:	1-3 hours
Dry Time to Sand:	4-16 hours (<4 mils dry), 16-24 hours (>4 mils dry)
Shelf Life:	24 months (minimum)

REVISION DATE: April 12, 2021

TOTALBOAT

PHYSICAL DATA:	
Vehicle Type:	Epoxy Resin
Components:	Two
Finish:	Semi-Gloss
Color:	Off White or Gray
Mix Ratio (by Volume):	1:1 (1 part base to 1 part activator)
Solids (by Weight) +/- 2%:	51% (Admixed)
Flash Point:	80ºF (Base), 64ºF (Activator), 61ºF (Reducer)
Theoretical Coverage (sq ft/gal):	400 @ 2 mils dry
VOC (Admixed):	< 420 g/L
Viscosity (Ford #4):	45 +/-5"

Note: The technical data sheet is reference the application and physical data of the primer. From "2-Part Epoxy Primer", 2021. (https://www.totalboat.com/product/2-part-epoxy-primer).

FIGURE 6

Bondo FiberGlass Resin Technical Data Sheet

Typical Physical Properties		
Container	One quart metal can one gallon metal can	22cc tube
Base	Unsaturated Polyester Resin, Styrene Monomer	Dimethyl Thalate, Methyl Ethyl Ketone
Density lbs/Gallon (Appx.)	9.35+-0.25	N/A
Color	Purple/Amber/Brown	Clear
Flash Point - °F	89 deg. F (closed cup method)	>200F (closed cup method)
Viscosity (CPS) Brookfield Viscometer	3000-6500 cps @2.5 rpm 1400-2200 cps @20 rpm	N/A
Service Temperature - °F	Min.-20deg.F Max.180deg.F	N/A

Performance Properties	
Work time:	8 minutes with 1.10% hardener @ 77 F
Sand time:	60 minutes 1.10% hardener @77 F
Lap Shear Steel to steel:	ASTM D3163-84 2100 PSI +-100 PSI
Lap Shear Aluminium to Aluminium:	ASTM D3163 600 PSI +-100 PSI
Water Absorption:	ASTM D-570 0.30% +- 0.05
Tensile Strenght:	ASTM D638-82 5800+-100PSI
Recommended Hardener/Resin ratio:	.75% to 2% by weight
Shelf Life:	One year from date of manufacture @ 65 -80 deg. F

Note: The technical data sheet is used to determine the work time as well as the cure time of the resin.

From “Keicher, 2007” (https://multimedia.3m.com/mws/media/466044O/tds-3mtm-fiberglass-resin-05833-05834.pdf).

FIGURE 7

Carbon Fiber Product Data

HexForce™ 284 ZB Prime Tex®

Carbon Fabric

Product Data

Style 284 ZB Prime Tex®		US System	
Type of Yarns	**Warp Yarn:**	3K Carbon, 33MSI	
	Fill Yarn:	3K Carbon, 33MSI	
Fabric Weight, Dry		5.70 oz/yd^2	193 g/m^2
Weave Style	2/2 Twill		
Finish	ZB		

Construction			
Nominal Construction	**Warp Count:**	12.5/in	4.92/cm
	Fill Count:	12.5/in	4.92/cm
Fabric Thickness		9.1 mil	0.23 mm

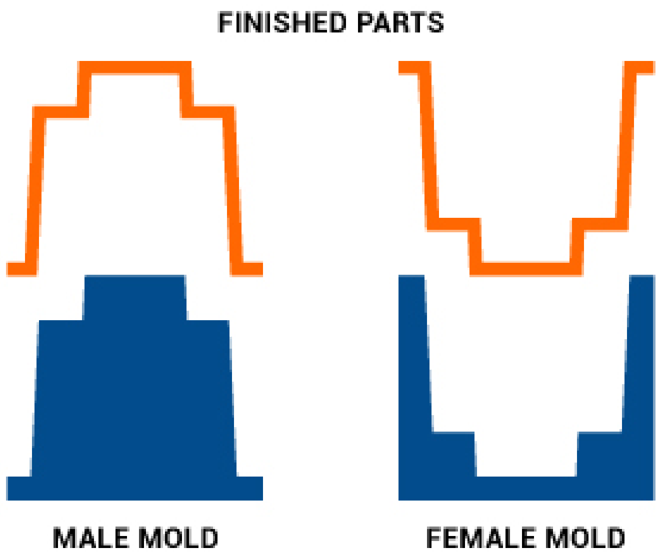
Note: The carbon fiber properties sheet can help when determining the fiber to resin ratio for maximum strength calculations. From "HexForceTM 284 ZB Prime Tex Product Data", 2014. https://compositeenvisions.com/wp-content/uploads/2018/03/284-ZB-Prime-Tex-TDS.pdf.

Plug and Mold

To create the carbon fiber dash of R.O.S.E a wet lay-up was pulled from a mold. A wet layup is a type of method used to lay composites. The resin is brushed onto the fiber with a brush on a separate surface and then laid onto the mold. At times one may opt to cover the resin saturated fiber with clear plastic, but it is unnecessary. Once the resin has cured, the composite piece is pulled from the mold. This method is the simplest and cheapest open mold fabrication process considering aside from the resin fiber and mold, all you need is a brush. The process of making the mold, also called compositing tooling, can vary. The method used here is called a plug and mold method. The male mold, also known as the plug, was modeled, and fabricated and from this a female mold was made (see *Figure 8*). It was from the female mold that the wet layup was pulled to create the dash

Figure 8

Male and Female Mold



Note: How the composite tools of the dash were constructed and distinguished. From "Mold Construction Guide", n.d.. https://www.fibreglast.com/product/mold-construction/Learning_Center.

The modeling of the plug was done in Sketchup by combining layers of blue foam board and modeling each layer. Once the modeling was complete the foam boards were cut to their own individual measurements using a hot wire foam cutter. The layers were then glued together with a Loctite General Performance Spray Adhesive that would not dissolve the foam (while there was some dissolving, it was not enough to be a problem). Once all together, TotalFair Epoxy Fairing Compound (see *Figure 5*) was used on the surface of the plug, after approximately 2-3 hrs @ 80°F the fairing was ready to be sanded. The surface was then sanded by hand to 2000 grit.

Two coats of TotalBoat 2-Part Epoxy Primer (see *Figure 7*) were brushed on by hand. After a dry time of 1-3 hours, the second coat was ready to be brushed on. Then after 16 hours after the second coat, the surface was sanded to 2000 grit.

Now, the mold release process starts. The plug was then buffed by placing a wool compound pad on a pneumatic random orbit polisher and a Rubbing Compound. Next, Collinite 900 Mold Release Paste was hand applied using a wipe on and wipe off method. When the mold release was wiped on, 30 minutes were waiting before wiping off again. This was done three times. Once the waxing was complete a PVA film part #10 was sprayed on to the mold with a HVLP spray gun at 22-24 psi at a distance of 12 inches. A thin coat was sprayed on, making sure to avoid spraying on too much to where it would drip. This would lead to improper drying. Once the PVA dried into a film (about 30-45 minutes) another 3 coats of wax were wiped on and off, waiting the 30 mins between again.

After all the drying and waiting, creating the female mold begins. This starts with creating the surface face with Gel Coat (see *Figure 9*). It was found 20 drops of MEKP per ounce of gelcoat work best, for bigger mixes, 20 per ounce (or 2% of MEKP). Three coats were brushed on the plug. Curing time between coats varied (2-5hrs), depending on the workspace temperature. The temperature should be at 70-95°F to allow for proper curing time. Each coat must be fully cured before the next coat can be brushed on. Improper curing can lead to shrinkage, which is when the surface is no longer smooth and creates little ripples along the pieces, possibly ruining the mold. Next, the reinforcing fiberglass of the female mold. Matte Fiberglass was chosen for its easy application and flexibility on corners. A Fiberglass Resin was used for its fast cure time see *Figure 6* for curing and handling properties. The resin has a work time of about 20 mins, this is notable when the resin starts to look and feel like sap. Best to do the process in an open space or outside so the smell is dissipated. The matte fiberglass was laid on the plug and the resin were brushed on. Three layers of fiberglass were done to create some rigidity with enough flexibility to allow to easier pulling off. No need to wait between layers.

Figure 9

TotalBoat Marine Gelcoat Technical Data

APPLICATION DATA:	
Application Method:	Brush, Roll, Spray
Thinner:	Styrene – Should not be required for most brushing/rolling applications, avoid adding more than 15% (it may cause yellowing), Sea Hawk Patch Aid 8185, and Dura Technologies Duratec®
Catalyzation Percentage:	2% MEKP, 9% Active (14-16 drops of MEKP per ounce, or 2 teaspoons per pint of gelcoat)** ** The acceptable range of catalyst is 1-3% based on ambient conditions and required working time. DO NOT use more or less catalyst with TotalBoat Gelcoat products.
Application Temperature/RH:	50-95°F (70-80°F is ideal), 0-90% RH
Viscosity:	5,000-8,000 cps (@ 77°F)
Thixotropic Ratio:	7.5-9.5
Application Thickness:	Roughly 5 mils per coat, building up 18-25 mils
Working Time:	10-15 min. (2% catalyst @ 77°F, 1 ounce)
Gel Time:	8-12 min. (2% catalyst @ 77°F, 1 ounce)
Peak Exotherm During Reaction:	335-400°F
Coverage (sq ft/gal):	12.8 sq. ft. @ 1/8" *** 25.7 sq. ft. @ 1/16" *** 51.3 sq. ft. @ 1/32" *** *** Does not include any material wasted from application; generally 10-15% is wasted.

PHYSICAL DATA:	
Vehicle Type:	Unsaturated Polyester Resin
Components:	2 - Resin, MEKP catalyst
Specific Gravity:	1.1-1.4
HDT:	185-205°F
Flash Point:	88°F
Storage:	Store below 75°F, and away from heat sources and sunlight. Store in a cool, dry area away from flames or heat sources. Keep the container completely sealed.
Shelf Life:	6 months from date of manufacture
VOC:	<400 g/L

Note: This technical data sheet specifies how the gelcoat can be applied and stored. From "Gelcoat", n.d.. https://www.totalboat.com/product/gelcoat/.

After the resin has cured, the plug is ready to be pulled off. In *Figure 10* the side profile of the plug is visible, along with the edges where it was attempted to remove the plug from foam. Due to the complexity of the mold, the piece had to be cut in half. The spot with most curves, corners, and complexity was chosen to allow more access to those edges (see *Figure 11*).

In *Figure 12* the plug is seen pulled off. Next a flange was created out of fiberglass where the cut down the middle was to re-attach the two halves for the wet layup (see *Figure 13*).

Figure 10

Side view of male mold with fiberglass on, foam layers visible as well

Note: This view of the dash allows the viewer to see the layers of foam, which give more insight into the construction of the plug. From Navarro-Luviano, 2020. Photograph.

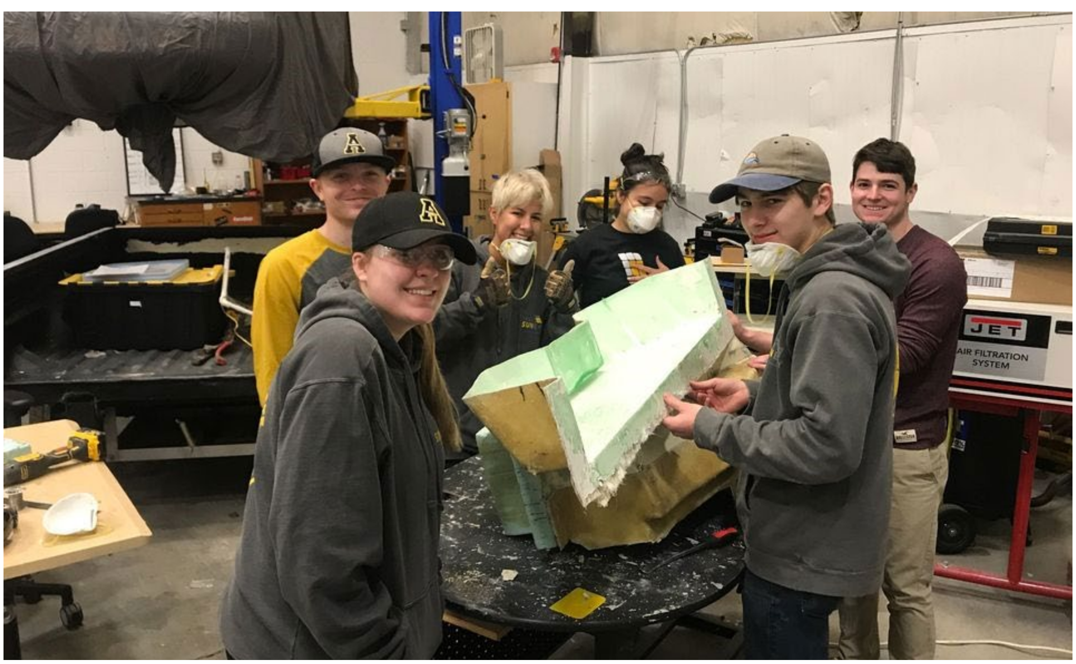
Figure 11

Line marking where the piece had to be cut to remove the finished fiberglass part.

Note: The red dotted line represents where the plug was cut to allow easier access when pulling the composite material off. From Navarro-Luviano, 2020. Photograph.

Figure 12

Fiberglass part pulled from male.



Note: This was an important moment when the fiberglass female mold came off the plug. From Tolbert, 2020.https://www.facebook.com/appstatesvt/photos/pcb.1547046675434590/1547046412101283. Photograph.

Figure 13

View from top of female mold highlighting flanges

Note: With the two halves together one can clearly see how the flanges allow for easy assembly and disassembly of the mold. From Navarro-Luviano, 2022. Photograph.

To fix some imperfections in the plug more fairing was added, and the surface was sanded to 2000 grit. The mold release process is then repeated on the female mold. The female mold is then ready for the layup. The flanges are secured with bolts and clear duct tape is placed over the seam of the two halves.

WET LAYUP METHOD

Using the Fiberglass Resin, a wet layup with 3k Carbon fiber 0/90 weave was done (see *Figure 7*). First, 2 large carbon fiber sheets were cut into 5 sections each to create the 2-ply piece. Then, the carbon fiber was laid on a table covered with saran wrap and Fiberglass Resin was brushed onto the fabric at 45 degrees as to not disrupt the 0/90 weave of the carbon fiber. Resin was also brushed onto the mold. With a team of three, the carbon fiber was carefully laid onto the mold. This was quite difficult considering the fabric had now become an exceedingly elastic like material that was hard to control. With carful placement, the rest of the carbon fiber was laid on. Saran wrap was then used to cover the exposed side of the wet layup. In total, two ply of carbon fiber was done and various large section pieces in certain areas and this took about one hour to complete. The mold was left to sit for a total of 12 hours before being unbolt and the finished carbon fiber piece was pulled off. The first mold was produced of carbon fiber (*see Figure 14*). If molds do not sustain sufficient damage, the surface which they were pulled off can be used 2-3 more times.

WET LAYUP OBSERVANCES

As evident in the surface of the part marked by red circle in *Figure 14*, there were dry areas that did not receive sufficient resin, while other spots were heavy with resin. These dry spots are known as voids. While a wet layup may be the easiest process with minimal materials needed, it is not the most effective at producing a reliable piece. This is due to the variability of applying the resin. When doing the layup, fearful of these voids an excess amount of resin was used. Not only was resin brushed onto the carbon fiber but was brushed onto the mold as well. Once on the mold, the brushes were used to press the resin into the carbon fiber, with hopes of the resin seeping through.

Figure 14

First finished piece pulled from the female mold

Note: The first carbon fiber dash is produced, but with many voids and unsatisfactory surface. From Navarro-Luviano, 2020. Photograph.

Vacuum Bagging Method

The West System (2010) Vacuum bagging manual states that vacuum bagging (or vacuum bag laminating) is a clamping method that uses atmospheric pressure to hold the adhesive or resin-coated components of a lamination in place until the adhesive cures (p.2). A vacuum pump creates a vacuum to consolidate the laminate plies together using an airtight envelope. Both pressure on the outside and inside of the bag are equal to atmospheric pressure, 14.7 psi (Carruthers, 2018). This evacuation of air creates equal and even pressure on the surface of the envelope which in turn presses the resin evenly across the surface. Due to the even distributed pressure, fewer voids are created. Vacuum bagging also allows extreme flexibility with laminated parts being consolidated in terms of dimension and surface as well as shape. When envelope bagging, that is when the tool is completely in the bag and pressure is on both sides, the tool needs just be strong enough to hold the laminate in place until cured (West System, 2010).

Benefits of vacuum bagging include a better upper face finish, the surface that will be seen, and this is due to the even and equal pressure on the surface of the mold as well as making degassing easier. Degassing is essentially the removal of bubbles formed in the resin mixture which is in conjunction producing far less voids (Mouritz, 2012). The control of resin content allows for a higher fiber to resin ratio which directly translates to high strength to weight ratio. The next steps in working with composites for the team is to learn how to improve our methods. Vacuum bagging proves to be the next logical step in producing composite pieces that perform and look better. After intensive research the necessary materials needed for a vacuum bagging were discovered and are listed below.

- TotalFair Epoxy Fairing Compound
- TotalBoat 2-Part Marine Epoxy Primer-Build Primer
- Abrasive (80, 120, 220, 400, 600,800 1000, 2000 grit)
- SM5142 Tacky Tape
- 1 Wicks Aircraft Valves
- 2.5 CFM 1/6 HP One Stage Vacuum Pump Air Conditioning HVAC
- Hexcel HexForce Carbon Fiber Fabric 2×2 Twill 3k 5.8oz/197gsm Style 284 with Primetex Finish
- Nylon Release Peel Ply
- Release Film
- Bagging Film
- Breather and Bleeder Cloth
- Polythelene Hose
- PVC

- Barb fittings
- Hose Clamps
- Pressure Gauge

The male mode has now been used two times and due to low quality of the surface, a new surface was created and prepared. This new surface was done by brushing on new primer onto the surface of the female mold. In preparing for a vacuum bagging, the female mold was repaired of any voids and damages. This included filling voids with fairing and sanding down with 200 grit. Once sanded, the whole surface is covered by brushing on TotalBoat 2-Part Marine Epoxy Primer-Build Primer. Two coats were done, with hand sanding to 2000 grit after 16 hours of the last coat. Next the same mold release process as the previous was done. This included using a wool compound pad with a rubbing compound to polish the surface, three intervals of wax on and wax off, a thin coat of PVA film part #10 was sprayed on, and three more intervals of wax on wax off.

The first ply of carbon fiber is cut into two large pieces; since the first ply will be the upper surface, having it be as much of a single piece was crucial for improved looked. The second ply was cut into 5 easier handling pieces and the final ply was a combination of various sized pieces. Next the carbon fiber was laid on a large worktable in preparation for the Fiberglass Resin. Due to the 15-minute worktime of this resin, only 3oz batched of resin were made for each ply. As opposed to brushing on the resin, it was poured over the length of the carbon fiber sections. The resin was then spread throughout the fiber with a flexible plastic scraper being sure to leave no surface dry, or lacking resin. Once all saturated, the fiber was lifted and moved with a team of three to the mold and carefully placed in the desired position. The first ply will be the visible one, so extra care was done to move any loose fiber threads on the mold surface. The next two ply were also coated and placed with the same process.

Now the vacuum bagging process starts. First a layer of peel ply is played on the whole surface, with sections being cut to best cover every spot allowing for overlap. This material is meant to allow for the excess resin to soak this fabric like material. The possibly of the peel ply depriving the composite pieces of resin is always a concern when doing a layup on a piece that has few plies, so extra resin is brushed onto the peel ply for safe measures. Then the perforated release film, which was cut into more exact pieces, was placed on the surface. This is since the tiny holes in the perforated surface could overlap and restrict excess resin flow through. Next was the breather ply, overlapping of this material is better as to not allow resin, that may have gotten as far at this layer, to get on the envelope bag and cause sticking that may prohibit the bag from forming to the mold. Lastly, was the bagging but the realization that the resin was starting to cure was evident in the carbon fiber hardening. This was largely due to the extended time it took to place the carbon fiber with worktime of getting it in the right position. With a complex shape such as the one we have, and the short work time of the resin this was inevitable. However, the process had to continue, and so the bagging was next. The entire mold was lifted into a tube bag that had openings on either end. The bolts on the flanges were covered with tacky tape and cloth rags were strategically placed along the flanges edges to prevent rupture of the bag from the harden fiberglass exterior. Tacky tape was placed on both ends with three pleats each to allow extra travel room for the bag where the mold deepen (see *Figure 15*).

Figure 15

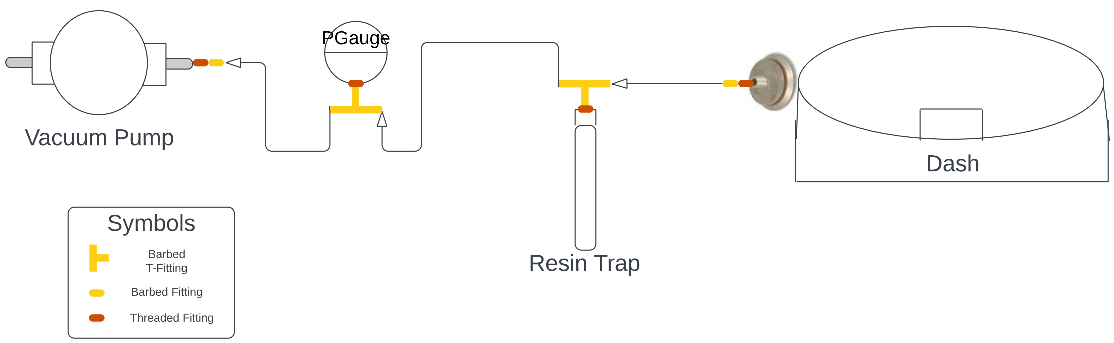
Tacky Tape Pleats

Note: The pleats in vacuum bagging are important to allow the bag more travel room than the width of the bag, especially for female molds with a hollow center like the once constructed. From Navarro-Luviano, 2022. Photograph.

By this point in the process, an excessive about of time had paced. As hour four was approaching the resin was curing but the process was continued to see the end product. As showed *in Figure 16*, a schematic of the connections from the dash mold and to the vacuum pump is shown. The vacuum valve is the point on the layup that the air is being pulled out, from there the hose goes to a resin trap where excess resin is captured as to avoid it entering the pump. The pressure gauge is used to observe the pressure on the composite piece, ideal pressure is 14.7psi since that is atmospheric pressure. From here it goes into the vacuum pump. However, problems arose when the vacuum did not pull any air out of the envelope bag. All connections were checked and retightened but with no success. The pump was pulling a slight pressure to where if one rested their finger at the hose end, the suction could be felt.

Figure 16

Schematic of Vacuum Bagging Connections



Note: This schematic of the setup is to illustrate how everything was originally connected before it had to be reduced to just a connection from the pump to the vacuum valve on the dash. From Navarro-Luviano, 2022. LucidCharts.

The decision was made to reduce the configuration as much as possible as to avoid any leakage. Since the cure time had already passed at this point, the resin trap was removed. And since the pressure would be uncontrollable with the specific vacuum pump on hand anyways, the gauge was also removed. In *Figure 17* the new configuration is seen with the hose going from the vacuum straight to the vacuum valve on the composite piece.

Figure 17

Mold in Envelope Bag

Note: In the image above a depiction of the vacuum bagging set up is shown. The connection is the reduces on of just having the hose go from the vacuum pump to the vacuum valve on the dash. From Navarro-Luviano, 2022. Photograph.

Even after all the connection reduction, the vacuum did not pull after one hour of trouble shooting and another hour of letting it sit to see if it may have been just a slow pull. These results were extremely disappointing seeing that the crucial moment did not turn out as expected. However, all the components and materials were right and the set up was exactly as supposed to be, from the resin application to the peel ply, release film, breather, envelope bag and tacky tape pleats. A second attempt was not able to be done due to limited supplies, but critiques and possible sources of failure can be theorized and replaced for future applications.

Critiques and Sources of improvements for Vacuum Bagging Failure

Soon upon working on laying the carbon fiber, the realization that having a short window of work time for beginners was not practical. The resin used, Fiberglass Resin, has a work time of 15-20 minutes meaning that once this time passes, the resin will be less liquid like and more paste like. This made it extremely difficult to adjust the carbon fiber on the mold as the resin hardened. For future considerations, utilizing not only an epoxy resin to properly enhance carbon fiber properties would be necessary but selecting one with a slow hardener. This will in turn allow for a longer work time. The next point of scrutineering is the vacuum valve. While the concept is simple enough it seems, this chosen valve could have been of low quality. Due to international shipping restrictions at the time, a more tested valve could not be ordered, hence the second-best option was this one from Amazon. While some review stated the valve worked perfectly others criticized it saying it did not hold a vacuum. It is quite possible the valve did not hold a vacuum in our case as well. Next possible source of error was in the fittings, from the barb and threaded fitting to the clamps and quick release. An odd observation of all the connections was the significant reduction in pressure from the opening on the vacuum pump itself to after the quick release. The difference in air pressure after the quick lease was quite noticeable. Due to limited supplies, no other connection could be attached from pump to the hose, so the quick release was necessary. A reconfiguration to eliminate the need for a quick release is possible. Lastly, the vacuum pump itself, 2.5 CFM 1/6 HP One Stage

Vacuum Pump Air Conditioning HVAC. The possibility that it was not equipped to handle the load demanded of it is slim considering its advertised to pull down to 75 microns and a typical vacuum bagging needs only 29 microns which convert to about 14 psi. Within the pump however lies another source of possible error, the fuel. The fuel the pump required was a low viscosity vacuum pump oil, the example the manual provided was HFV-46. Due to limited supplies once again, the choice to use an air compressor oil was made. This was also a low viscosity oil, however not a vacuum pump oil. The possibility of having over filled the tank creates doubt that if it was not filled past max, it would have work. When oil was removed the level did not change so the assumption was made it did not properly exhibit correct fuel level.

All these sources of possible error can be addressed for the second attempt. The most important on of all is using the proper resin with a slow hardener to extent the worktime. The connections and fitting could all work properly but if the resin starts curing before the vacuum pump process start, there could be significant failures again.

A tip that one could do and have troubleshooted these possible error before, was done a dry run of the equipment before the layup. This dry run of equipment would have been better managed of problems if it were not tested for the first time the moment of the vacuum bagging. While the layup did not reach the point of a vacuum bagging, it did fall under the qualification for a wet layup.

Conclusion

In conclusion, the reasons for doing a vacuum bagging are of enough importance and worth the effort to execute composite pieces with superior surface finish. Vacuum bagging yields a stronger composite piece due to the control and even distribution of the resin. The knowledge of how to not only do composite work right but improve methods used also adds quality in the work Team Sunergy does. This niche part of the team, composites, has drawn enough interest from new members to warrant efficient and effective techniques for composite improvements. The composite work field is rising, and this work can inspire team members to go into this industry, warranting a greater reason to learn how the professionals work with composite material, in this case, vacuum bagging. In *Figure 18* the incomplete vacuum bagging dash pulled from the mold is displayed.

Figure 18

Carbon Fiber Incomplete Vacuum Bagging Dash

Note: The carbon fiber dash that a vacuum bagging method was attempted but failed. Navarro-Luviano, 2022. Photograph

The outer ply was two sections of carbon fiber, with the smaller one being the hollow center and the other section being the rest of the dash. A scrapping on of the resin with scrapper as opposed to brushing on allowed for easier placement of the carbon fiber. Indentions can be seen in the bottom, as well as an indention in the top of the hollow center, this is due to bubbles that formed either from not being pressed down and held down, or fiber that got accidentally overly shifted. The vacuum that would have formed would have alleviated all these problems since an event distribution of pressure would have been on the carbon fiber. Although no voids are visible, the outer face is textured, meaning that the carbon fiber threads can be felt if one were to run their fingernail across the surface. This also would have been resolved with the even pressure the vacuum would have formed to push the resin through the fibers before the excess went through the other materials. While vacuum bagging would not have solved all the cosmetic issues such as the dust that got trapped upper the carbon fiber on the bottom left of *Figure 18*, the vacuum would have created a dash with a smoother surface and the even distribution of the resin would have alleviated the difference in texture of the surface.

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