METHODS FOR PRODUCTION OF CARBON-FIBRE-REINFORCED PARTS FOR A STUDENT VEHICLE IN SHELL ECO-MARATHON COMPETITION

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Abstract

Carbon-fibre-reinforced plastics have been extensively used in many sectors such as aerospace, automotive and civil engineering for numerous consumer and technical applications due to being strong, yet lightweight. Moreover, these plastics are not too expensive and do not require much tooling, big machines, or many workers in order to be produced with satisfactory final quality. This article briefly reviews the most common methods for their production (hand lamination, infusion, and prepreg) by emphasizing on advantages and disadvantages of each method, and by presenting an example of a carbon fibre monocoque coupe produced by university students for a small energy-efficient vehicle which takes part in the competition Shell Eco-marathon. Additionally, the sandwich structure for carbon-fibre parts, and production of moulds for the same project are shortly reviewed.

Keywords: *carbon, fibre, automotive, body, lightweight, Shell Eco-marathon*

1. INTRODUCTION

Carbon-fibre-reinforced plastic (or simply “carbon plastic”) is the most widely used composite in the automotive industry, being extensively applied in sports cars, supercars, and other vehicles with intriguing modern designs, as it makes them lighter, stronger and more aerodynamic. It can be moulded into almost any shape, and it also easily replaces various steel and aluminium parts. It is successfully implemented in automotive interior components, as well as rims, structural components, and body components [1]. Carbon plastic is even used for creation of whole vehicle bodies. Moreover, many parts have carbon plastic variants available on the aftermarket.

Carbon plastic is an intrinsic part of students engineering projects as well. It is applied in many of the vehicles that participate in the Shell Eco-marathon contest. The main aim of this competition is for students to design and build an ultra-energy-efficient car which travels the farthest possible with a set amount of fuel/electricity [2]. Certainly, in order to fulfil such a task, the vehicle body needs to be the most streamlined and lightweight possible. The used components and parts should also be lightweight and need to work as efficiently as possible. Such vehicles also require very precise energy management strategies as a means to achieve the longest feasible range. The competition is unique namely for the fact that it has inspired the creation of various novel vehicle designs [3-7], the usage of advanced materials such as carbon-fibre composites [8], and the usage of advanced production techniques such as 3D printing [9, 10], all done with the thoughtful inclusion of many students from schools and universities all over the world.

TUS Team, the representative of Technical University of Sofia in the competition, built the body of its latest vehicle entirely from carbon plastic and managed to lower its mass with approximately 10% compared to the old design, while bettering its durability and substantially improving its driving range – Fig 1. The production processes do not include any complex or big tooling and equipment, neither require too much workforce. Carbon plastic parts can be manufactured literally in every garage with satisfactory quality. This article aims namely at briefly reviewing the basics of the most popular methods for production of carbon-fibre-reinforced automotive parts and at presenting the production process of the vehicle's body of TUS Team, as a contribution to the global student engineering efforts in building the best next state-of-the-art, non-polluting car of the future.

2. COMPOSITE MATERIALS AND PROPERTIES OF CARBON FIBER

Composite materials, or just "composites", are such materials that are made of two or more constituent materials with different chemical and physical properties. Generally, the components of a composite are two – a matrix element and a reinforcing element (which can also be composed of a few materials) [11]. The main task of the matrix is to support the reinforcing elements and to maintain their exact position, while they, on the other hand, through their material properties, improve the overall properties of the composite. The wide selection of available matrices and reinforcing components allows designers to freely combine and realize composite materials with optimal properties that are suitable for a specific application. There are many known composites: concrete, plywood, reinforced plastics such as carbon and fiberglass, composites with metal and ceramic matrices, etc., used in the construction of buildings; the automotive, shipping and aviation industries, and generally in industrial processes where advanced materials with very high properties are used; as well as in household and medical products [11]. Composite materials are lighter, stronger, and more resilient than their individual components.

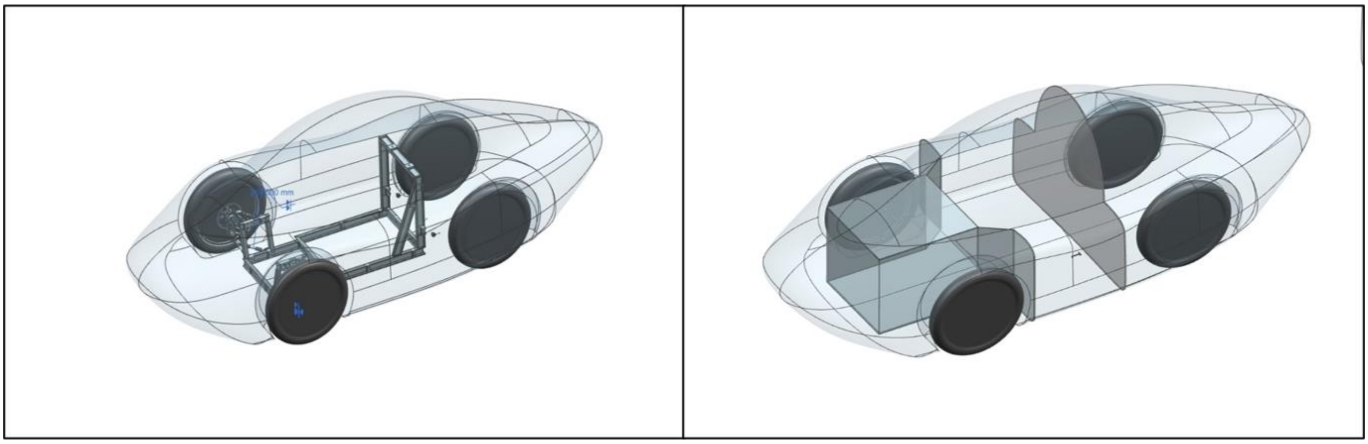

Figure 1. Old vehicle body from plastic and with aluminium frame (left) vs lighter new vehicle body from carbon with load-bearing carbon walls (right).

Composite materials must acquire a certain shape in order to be used, therefore a mould or a mould surface is required for their production. The matrix element can be laid in the mould before or after the reinforcing one by using different methods to form the final product, guaranteeing specific properties and proportions of the constituents. Commercially available composites use polymers for their matrix - polyester, vinyl ester, epoxy resins, etc., while fibres - glass, carbon, Kevlar and others, as a reinforcing element. The binding of the two elements is realized generally through heating and pressurizing.

Carbon fabric – Fig. 2, which is the reinforcing component of carbon plastic, consists of thousands of threads – carbon fibres, with a very small diameter - about 5 to 10 micrometres, which are black in colour and are made up from carbon atoms that are arranged in a somewhat similar fashion to the atoms of graphite (in a hexagonal shape stacked up in sheets). The raw material from which the fibres are made is called a precursor, with around 90% of the fibres made from polyacrylonitrile (PAN), while the rest produced from petroleum pitch – both organic polymers [12]. The difference of the final variation of carbon fibre is in the manner in which the atom sheets interconnect, and this consequently influences the nuances in the final properties. Fibres made from PAN have higher ultimate tensile strength in comparison to those from petroleum pitch, that possess higher thermal conductivity and stiffness.

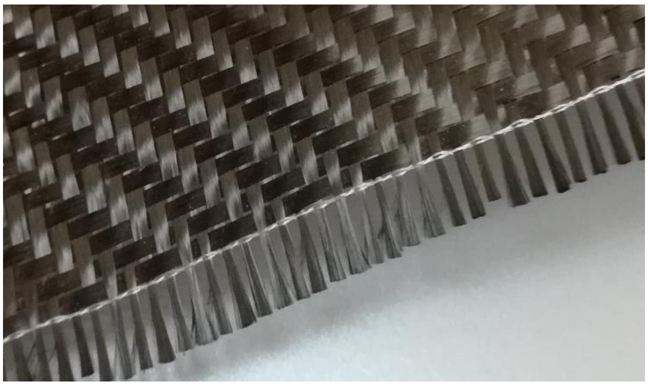

Figure 2. Carbon fabric.

Overall, the manufacturing process of carbon fibre is lengthy and complex. After preparation of the precursor, it is spun into fibres, washed and stretched thin. Then, it is stabilized in order to convert the linear atomic patterns into more stable ladder ones at temperatures up to 300 °C. Carbonizing is the next process which heats the fibres up to 3000 °C (or less depending on the type of fibre desired) in high pressure anaerobic surroundings in order to expel the non-carbon atoms from the structure, this way the material achieves its black colour. Then, the fibres are treated additionally by being oxidized for better bonding properties, and rolled up on cylinders which are called bobbins [13] – Fig 3.

Figure 3. Carbon fabric on bobbins [13].

The physical properties of carbon fabric are largely determined by the degree of carbonization - amount of carbon in the thread, which is normally more than 92% of the total mass, and also by the relative orientation of the layers to each other. The main variation in commercial fabrics is strength at the expense of stiffness and vice versa. The fibre has the following general characteristics [14]:

- high specific strength – approx. 2400 kN.m/kg;
- high modulus of elasticity;
- corrosion resistance;
- fatigue resistance;
- electrical conductivity;
- fire resistance and non-flammability;
- high thermal conductivity in some of its forms;
- low coefficient of thermal expansion;
- biological inertness;
- lack of toxicity;
- X-ray permeability.

The carbon threads have a certain direction and are arranged in one or several layers, forming the fabric. Depending on the number of layers and the directions and thickness of their threads, the fabrics are divided into unidirectional and multidirectional. The individual fibres and layers are protected and connected to each other by organic coating, for example polyethylene glycol, in order to prevent formation of waves, which may often lead to mismatch with the desired shape of the finished part. The coating also guarantees greater strength of the fabric and does not allow the individual threads to unstitch.

By being rolled up on a bobbin, the fabric is easy to transport, store and cut. An important feature of it, depending on the number of layers and the size of the threads, is its weight per square meter. It determines the thickness, applicability, and cost of the fabric [11].

The most popular matrix component used for manufacturing of carbon plastics is epoxy resin. When mixed with a hardener in certain proportions, it forms a thermally reactive polymer. This polymer has good mechanical strength and is resistant to chemicals and heat. The epoxy itself is sensitive to sunlight so it needs to be stored away from it.

By applying the carbon fabric and the epoxy-hardener mixture together via a specific method the carbon fibre plastic parts are produced – Fig. 4.

Certainly, using such parts, and manufacturing them, has its disadvantages:

- relatively high price of fibres for usage in massive scale production;
- time consuming production processes;
- brittleness and propensity to cracks of the final composite products;
- handling of toxic products (resin, hardener) and emittance of toxic particle matters during additional treatment of carbon plastics (when sanding).

Nonetheless, the advantages compensate many times for the drawbacks and that is why carbon fibre is so popular in the automotive industry.

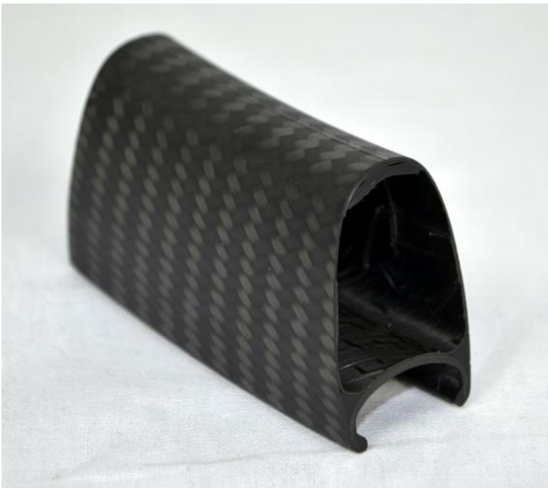

Figure 4. A ready-to-use carbon part [15].

3. METHODS FOR PRODUCTION OF CARBON-FIBRE-REINFORCED PARTS

3.1. Hand lamination

Hand lamination (also known as “hand lay-up”) is one of the most popular and simple methods for producing carbon parts. When hand lamination is applied, the individual pieces of carbon fabric are placed in the mould or on a surface of the mould one by one in a particular arrangement of the threads which determines the size and direction of forces which the final product would be able to absorb. Of great importance for the quality of the final product is namely the precision with which the fabrics are laid down in the mould. It is also important to apply in advance a special separator gel between the first layer and the mould surface, in order to guarantee easy separation of the two objects in the end of the production process. Of course, the mould needs to be cleaned with a degreaser liquid before beginning the lamination process. When cutting the carbon fabric, its non-coated sides are taped so that the threads do not unstitch. A mixture of resin and hardener is applied between the individual fabrics and the mixture ratio depends on the type of resin, but the basic one is for every 100 grams of resin - 25 grams of hardener, thus 4:1. Mixing is done by stirring thoroughly for a few minutes and it is recommended to be at the temperatures with highest noted hardener efficiency, most often standard room temperature. Rollers and brushes are usually used to apply the separator gel and the resin-hardener mixture – Fig 5.

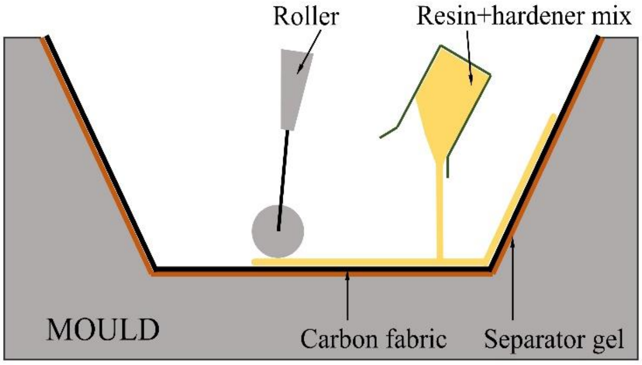

Figure 5. Carbon fabric hand lay-up.

Once all the fabrics are positioned correctly, a layer of peelply is applied, which distributes the resin more evenly on the carbon fabrics and makes the last layer of the part stronger and with better finish appearance. This is then followed by vacuum bagging – placing of cotton wool and vacuum nylon (Fig. 6), which at their ends are sticked tightly to the mould with a special type of vacuum tape, that also well preserves the surfaces of the mould. A hole is cut in the nylon and the vacuum pump is mounted to the hole through a vacuum valve. The cotton wool ensures that the resin reaches everywhere in the vacuumed package and it also absorbs the excess resin.

Figure 6. Nylon and wool for vacuum bagging.

The next steps are to vacuum the package at room temperature for 24 hours – Fig. 7, and then bake/cure it in an autoclave or an oven together with the mould at 80 °C for 16 hours. The temperatures and preparation times may differ depending on the type of resin and the recommendations of the resin's producer. The finished part is removed from the mould, cleaned, sanded to remove excess debris, and to obtain a better finish appearance – polished and varnished if necessary. This method can also be used with other reinforcing components in the composite - fiberglass or Kevlar for example.

Figure 7. Vacuum bagging.

3.2. Infusion

The infusion method is a more difficult technique for production of carbon parts, but a very effective one. The materials used are different from those in hand lamination: the resin has low viscosity, the hardener is slowly-reactive, and a special infusion network with hoses and connectors is used. The ambient temperature during the production process is recommended to be standard room temperature.

The production steps are basically the same as in the lamination technique, but with a few small differences - the mould is cleaned and smeared with a separator, then the carbon fabrics are placed carefully in the desired pattern, but without applying the mixture of resin and hardener. Then, the peelply and the infusion network are applied. The whole working surface is edged with special spiral hoses, via which the resin is distributed throughout the volume of the mould, while the connectors are used for the resin to flow in and out of the package. Then, the vacuum nylon is placed, which must be glued very tightly with vacuum tape in order to prevent formation of gaps. The connectors are connected via additional hoses to a container with resin and the vacuum pump, which are respectively the inlet and outlet ports of the infusion package. Usage of cotton wool is not necessary since the excess resin is drawn from the package by the infusion network. It is important to place an additional resin tank before the pump where the resin is going to be collected, in order to protect the pump from being damaged. Thus, by sucking out the air from the package, the pump forces the resin to distribute itself gradually and evenly to all points of the laid fabrics.

After the infusion process is completed, the vacuum needs to be maintained for about 24 hours. Then, the inlet and outlet ports are closed and the part is baked together with the mould at 60 °C for 16 hours, although these parameters vary depending on the type of resin used. After that, the part is separated from the mould and undergoes post treatment to better the quality of the surfaces. The parts created with infusion have better quality than the ones made with hand lamination, since the resin is dosed more precisely. The process may be a bit more expensive, though, and also requires higher qualification.

3.3. Prepreg

The prepreg method (abbreviated from pre-impregnated) is among the most advanced ones and is applied for the faster production of a greater amount of carbon parts. In this method the carbon fabrics are soaked with resin in advance and prepared to be directly laid in the mould and laminated, hence the name. Prepregs can be stored for a few months at room temperatures, but keeping the material cooler, can preserve its characteristics and quality for longer times. The standard resin content of the prepreg package is 35-42% depending on the producer, and the reinforcing component can also be fiberglass or Kevlar, or a hybrid carbon-Kevlar one [12, 16].

This method has many advantages: exact machine dosing of the resin, easy placement of the prepreg in the matrix, fast hardening during the heating process, smooth finish surfaces after separation, many times without the need for varnishing and polishing. However, curing such parts should be done at temperatures of 80 - 130 °C, or even higher, therefore a heat-resistant mould is required, and depending on the type of prepreg, it can be performed in an autoclave or in an oven. The separator must also be suitable for high temperature use. With the exception of these features, everything else regarding this technique is done as in the usual vacuum bagging of carbon parts which is performed after laying the prepreg in the mould.

The technique can be significantly more expensive than the other methods, however. It is also important that the package is fresh - slightly sticky, neither too moist, nor too dry. It should also always be left for some time at room temperature to acclimatize before beginning the work process, if it is previously cooled.

In Table 1 are presented the advantages, disadvantages, and some other general characteristics of the mentioned methods.

3.4. Sandwich

The sandwich structure is another interesting option for creating carbon surfaces and walls, which is based on the hand lay-up method. In this case several layers of fabric cover a honeycomb that is made of materials based on cellulose or aramid, thus achieving high specific strength, giving more volume to the wall of the part, and bettering its vibration damping capabilities – Fig. 8. There are honeycombs of different thicknesses, but most often for medium-sized products is used the five-millimetre-thick one. The manufacturing process is almost the same to that of manual lamination: 2 to 3 layers of fabric are arranged in the mould, coated with resin, vacuumed and cured. The finished fibre surface is separated from the mould, then smeared with resin again, the honeycomb is placed on it and at its other side a few new layers of fabric are added, thus forming the other surface of the wall. Those additional fabrics that come on top of the honeycomb should be soaked with resin separately from it in advance. Vacuuming and baking of the part follows.

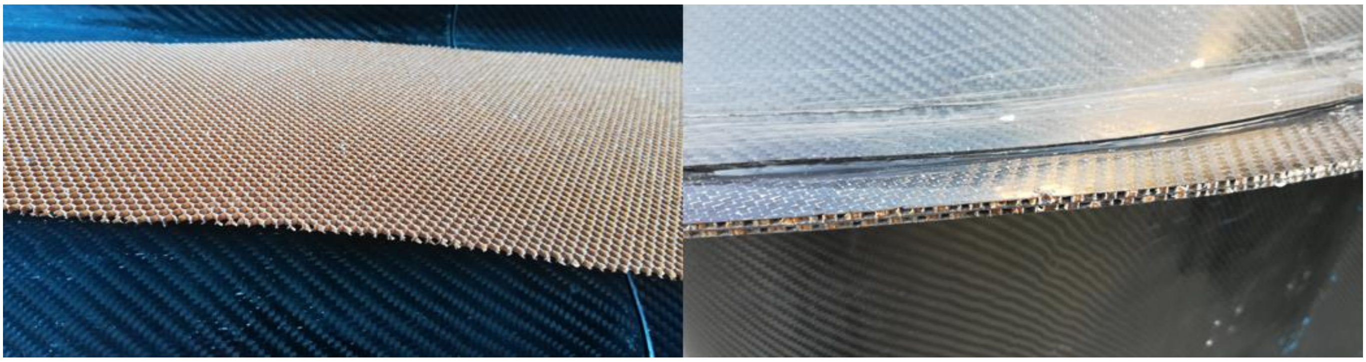

Figure 8. Five-millimetre-thick aramid honeycombs, separate (left) and incorporated in a ready part (right).

Table 1. Comparison of all mentioned production methods [14, 16].
Legend: C=Complexity, Q=Quality, RP=Relative price, (+)=lowest, (+++)=highest.

Method	Advantages	Disadvantages	C	Q	RP
Hand lamination	- Low-cost tooling and generally the cheapest method; - Simplest method, easy mixing of different types of fabrics.	- Worst strength properties, worse surface finish than infusion and prepreg. - Long production times. - Excess resin, a messy process.	+	+	+
Infusion	- Medium cost with satisfactory quality. - Cleaner production than hand lay-up.	- Higher complexity than the other methods.	+++	++	++
Prepreg	- Maximum strength properties, because of evenly distributed resin; - Repeatability in quality; - Less waste and mess; - Faster production times; - Better final cosmetics of the product.	- Higher cost; - The prepreg has a certain lifespan; - Higher baking temperatures, so a heat-resistant mould is necessary.	+	+++	+++

3.5. Making moulds

In order to produce a carbon-fibre product, it is firstly necessary to have a mould. The mould could be made as a polystyrene model and sealed with a special paste or gelcoat, as the standard resin for carbon fibres normally melts polystyrene. The gelcoat is a modified resin used particularly for moulds which guarantees high-quality surfaces. It is characterized by high wear resistance, hardness and strength, which makes it suitable for making long-lasting moulds. First, a separator is applied on the model, and then the gelcoat - it dries for about 4-5 hours, but it is best to work on the mould after 24 hours to be sure that the material is completely hardened. Then, fiberglass fabrics are laid on gelcoat layer, soaked in a mixture of special resin for moulds and about 2-3% hardener, which are also left for 24 hours to harden. This type of resin has a special feature - it does not emit large amounts of heat during the process, and curing is not required. Finally, the surfaces of the mould go through wet sanding to achieve higher finish quality, which reflects on the roughness of the surfaces of future parts made by using the mould.

4. EXAMPLE PRODUCTION OF SHELL ECO-MARATHON VEHICLE MONOCOCQUE

The Phoenix vehicle was designed and produced by TUS Team students, achieving an extremely low drag coefficient of 0.136, thus ensuring minimum drag resistance during movement [17]. To determine this coefficient, a mathematical model was applied to a 3D model of the Phoenix 2018 coupe in a software environment – Fig. 9. The mathematical results were then confirmed experimentally in a small wind tunnel. The interior and exterior dimensions of the body are fully compliant with the regulations of the Shell Eco-marathon competition. The coupe of the new Phoenix vehicle is lengthened and with a lowered roof to further decrease the drag coefficient. Moreover, the inner aluminium frame is replaced with carbon-fibre walls as shown in Fig 1, thus lowering significantly its mass.

The used production method is hand lamination. The necessary materials are the following:

- carbon fabric;
- resin and hardener;
- separator gel;
- peelply, cotton wool and nylon for vacuum bagging;
- fiberglass fabrics and gelcoat;
- aramid honeycombs;
- additional materials and tools such as degreaser, glue, duct tape, vacuum tape, gloves, mask with a particulate filter, goggles, brush, roller, stirrers for making mixtures, containers for storing aggressive liquid materials, glue mixer gun, tools for cutting of the finished parts, sandpaper for wet and dry sanding, polishing paste, a vacuum pump, vacuum valve, hoses and containers for proper storage of excess materials that are to be recycled.

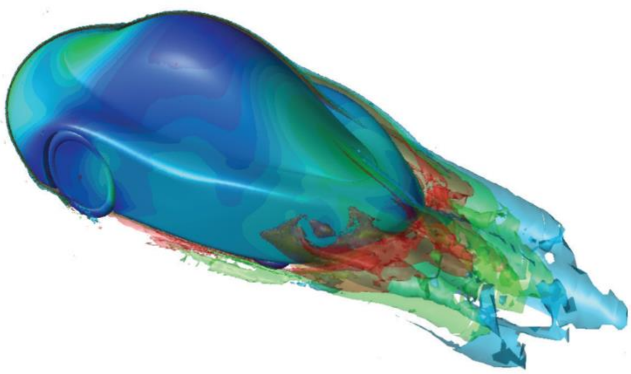

Figure 9. A simulation of the air flow around the model of the coupe.

The construction of the vehicle’s body was performed as follows:

Firstly, the moulds were prepared by cleaning them and by determining the surfaces which are not going to be laminated, such as windows, doors, stop lights and others – Fig. 10. These surfaces are marked with tape.

Then, successively in the mould are applied separator gel, carbon fabrics soaked with resin, peelply, cotton wool for the excess resin, and nylon for the vacuum bagging – Fig. 11. After vacuuming, the part is cured.

The cured coupe is then separated from the mould – Fig. 12, cleaned, and additionally treated before being assembled with the other parts such as the floor, section walls, and the front and back lids.

Figure 10. Cleaning and preparing the mould for hand lay-up.

Figure 11. Vacuum bagging of the laminated moulds.

Figure 12. Carbon-fibre coupe separated from the mould before treatment.

A separate mould is created for the floor and the section walls – Fig 13 and Fig. 14., as well as for the two lids, while the doors are created in the mould from Fig.10. The cleaned body without windows and the two lids is shown in Fig. 15, while the finished vehicle – in Fig 16.

Figure 13. Creation of polystyrene mould for the floor and section walls.

Figure 14. Separated from the mould and cleaned floor and walls.

Figure 15. Floor and walls assembled with the main body.

5. CONCLUSSION

The article deals with the description of the most popular methods for production of carbon-fibre-reinforced plastics: hand lay-up, infusion, and prepreg. The methods differ in cost and complexity but generally do not require much work force or complex tooling, and provide satisfactory quality of the end product, thus the production process can be performed in any garage or student laboratory. The brief comparative assessment of the three methods ranks their complexity, quality of the final product and cost of the materials and tooling used.

Figure 16. Final, assembled carbon-fibre coupe.

The results from building the carbon-fibre body of a student vehicle for the competition Shell Eco-Marathon are also presented. The students from TUS Team from Technical University of Sofia, Bulgaria successfully applied hand lamination to build their carbon coupe. Building of polystyrene-based moulds and aramid honeycomb-based walls was also applied to further developed the production skills of the students and to better the structure of the vehicle.

ACKNOWLEDGMENTS

The TUS Team project was funded by the Faculty of Transport of Technical University of Sofia and by all the sponsors and partners of TUS Team.

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