

Case Study of Composite Chassis Manufacturing Process Using Low Temperature Molds Tempered with Gradual Heat Annealing Process

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ABSTRACT

This case study describes a manufacturing process of composite chassis also known as monocoque. The structure is made using carbon fibre reinforced polymers (CFRP) which are manufactured in out-of-autoclave (OOA) process from pre-impregnated carbon fabrics and aluminium alloy honeycomb core. Since the material cost is high the aim of the project was to reduce the cost of manufacturing process i.e. cost of models and moulds. Therefore, instead of high-temp models and moulds a cheaper alternative was used. It consisted of Styrofoam models made using polyurethane (PU) paste and moulds made from CFRP using wet layup process which were cured at room temperature. Such moulds had to be adapted to withstand high temperatures during pre-preg cure. This was done with gradual heat annealing process which increased the maximum service temperature from 45°C to 90°C. This was enough for the low-temp cure of pre-preg material, but it might be possible to increase the temperature even further. As a result, the cost of manufacturing process had been reduced by 50%.

Keywords: monocoque; manufacturing; out-of-autoclave; manufacturing process; gradual heat annealing.

INTRODUCTION

The monocoque is a part of vehicle chassis developed first back in the 1960s in by McLaren F1 Team. Its main purpose was to protect the driver from impacts and serve as attachment structure for other systems (suspension, aero package, steering, electronics, etc.). Obviously, all the loads that are created in these systems pass through the monocoque structure. This exhibits huge stresses and deformations on the chassis, which needs to have sufficient strength and stiffness to resist them. On the other hand, the structure must be lightweight, as it is key requirement in motorsport racing. This was possible with carbon fiber reinforced polymers, which is a composite material that has changed many areas of engineering. The monocoque stayed with formula one and proved to be useful and as a result became popular in motorsport vehicles. In recent years it has been seen for first time in

commercial cars, mostly electric vehicles as the mass advantage justifies the additional cost of the structure. It is likely that the trend will continue thus research in the areas of both materials and manufacturing process is justified.

The goal of this project was to manufacture a chassis that would be compliant with Society of Automotive Engineers (SAE) standards for formula racing series. The design process of the chassis itself will not be described in detail, as it is not the scope of this paper, however a summary is as follows. It begins with numerous tests of materials in particular composite panels what will be used to create the shell of a monocoque. The panels can be made of various composite materials. There have been trials with basalt reinforced polymers [1], yet it is the carbon fibre that remains the most popular choice. Also, a range of materials can be used for the core of the sandwich panel. There are cases where the core is not used [2], but it is dictated by the application type such

as heavily loaded components which require high stiffness and strength. For the rest of the monocoque structure the sandwich core must be used as the carbon fiber has poor shear properties. A foam [3], PVC [4], Nomex [5] or aluminum honeycomb [6] are used. Usually, panels have a kind of aluminum core as it has been reported to have good energy absorption properties for the given thickness that is optimal for the structure. [7–9]. Basing on the literature and data sheets of available commercial products a few carbon fiber types and aluminum honeycomb core were selected for further tests. They included obligatory (required by the rules of SAE) perimeter shear and three point bending tests which determined the properties of a panel [9–10]. Basing on the results the Computer Aided Design (CAD) models were made together with structure analysis using Finite Element Methods (FEM). Usually at first it is beneficiary to prepare concept design and test it using FEM methods which accelerate the design process significantly as it has been done and reported in [12–14]. Moreover, the importance of manufacturing process must not be forgotten as it equally if not more important for the design to be properly made as well as cost and time effective. There have been a few approaches to this problem [15–17]. There were a few well documented designs in this field, utilizing various design philosophies, materials and manufacturing processes [18–20] and can serve as benchmarks and tutoring materials.

The manufacturing process was designed taking the chosen materials and CAD models. In case of manufacturing a composite structure, one needs molds from which molds can be produced or just the molds suitable for a given manufacturing process. Additionally, since the material chosen through tests was pre-impregnated carbon fiber, which utilized out of autoclave cure at high temperature it is required that molds must be able to withstand the given conditions without deformation. On top of it, to ensure geometrical accuracy of the final cured product, the thermal expansion should be as little as possible. Finally, only single product (monocoque) is being made using the molds since the vehicle is a prototype and only one piece is produced (or at least one piece with that geometry).

Those requirements create a major problem, as such molds are in general expensive due to the cost of high temperature materials and additional costs of machining such materials to create the models/molds. Also, low thermal expansion can

be achieved using only carbon fiber molds which must be made using an initial model on which the mold can be laminated. The goal of this research is to create an affordable manufacturing system, which would fulfil the conditions given above and compare it to the costs of creating other systems such as ones presented in [15] and [19].

METHODS AND MATERIALS

As mentioned above, the monocoque structure is constructed using composite panels. They consist of aluminum honeycomb core and 2mm carbon fiber skins. The carbon fiber used is a commercially available out-of-autoclave pre-impregnated carbon fiber called XPREG XC110 [21]. It is based on Pyrofil TR30S 3K carbon fabric with a 2×2 Twill 3K weave which is impregnated with epoxy resin in B stage. For the core material, an aluminum alloy honeycomb is used. It is a commercially available 5082 aluminum alloy honeycomb [22]. Its thickness varies from 10mm to 20mm at different areas of the structure which results from the design stage. To bond the core material to the carbon skins, a epoxy film adhesive is used. It is a 0.15mm thick, commercially available film adhesive called XA120 [23], which is compatible with both materials and to some degree limits the galvanic corrosion. Both carbon and adhesive film require one of cure cycles, which has been shown at Figure 1.

Therefore, molds created for the project must withstand the cure temperature and be stiff to preserve the design geometry. Also, since the mold will be moved from the workshop to the oven it should be lightweight, so that it can be transported by two people. This can be achieved by using composite molds as they offer excellent stiffness to weight ratio. Since the geometry of the product is complex one needs three separate molds to be connected together in order to achieve the final shape. This can be seen at Figure 2 where the two halves (green) are joined with a cockpit opening mold (black) in order to achieve a surface inside that corresponds to the geometry of designed structure. The molds can be created using a few approaches. The one most common for such projects is the one where models are machined from high temperature material such as epoxy boards. Next the molds are created using a tooling prepreg material which is laminated on the machined models and cured in the oven at high temperature.

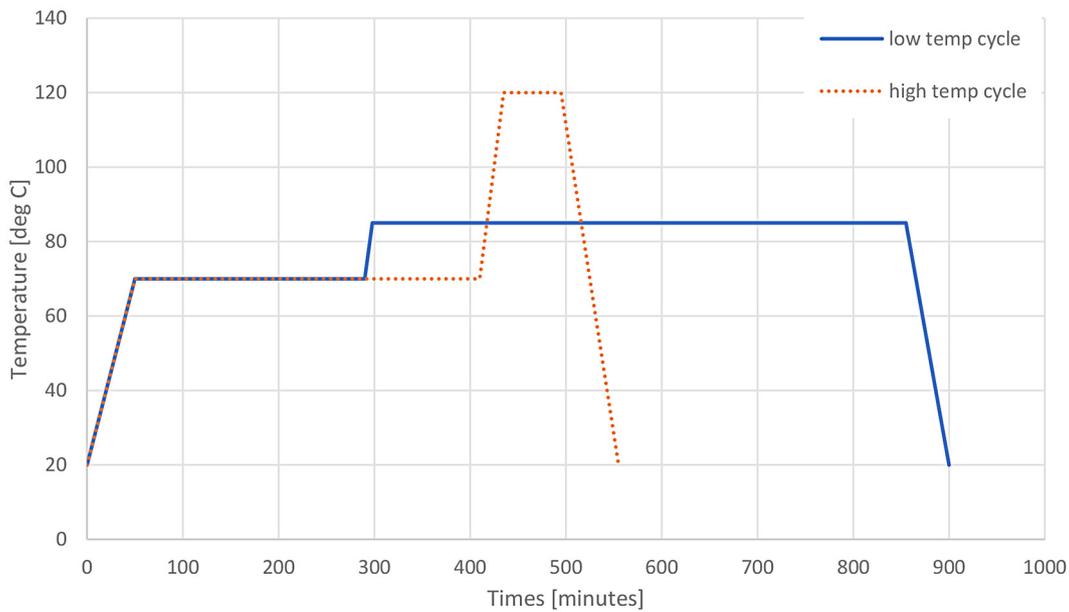


Figure 1. High and low temperature cure cycle for XC110 pre-pregs and XA110 film adhesive used in this project

This approach can be viewed at [24] However, in this project an alternative solution was used in order to reduce the tooling cost. The models were obtained by roughly machining Styrofoam block to required shape and applying thick layer of polyurethane (PU) mould paste [25], which was left to cure. The following step was to machine the paste to required shape using precise CNC machining techniques. Penultimately, the mould had been covered with thin layer of white polyester gelcoat [26], which was polished before fully curing. This layer also served as a barrier between polyurethane (PU) mould paste and the epoxy gelcoat used in the next step in mould manufacturing as PU could react with epoxy resin and its surface is highly porous. Such models can withstand 2–3 mould lamination cycles,

which is enough for the given case. However, they are not suitable for high temperature cure, thus a different approach to mold preparation is needed. The molds can be laminated using a wet layup technique and subjected to a process to temper them for high temperatures. It can be done with gradual heat annealing performed after curing the composite molds, which should increase their glass temperature.

Prior to the monocoque lamination a compatibility test has been conducted using smaller part (nose cone), which has proven that all used materials didn't cause unwanted reactions and most importantly the annealing cycle was effective. The scheme of the whole process can be simplified to the series of blocks (Figure 3) and each step will be commented briefly.

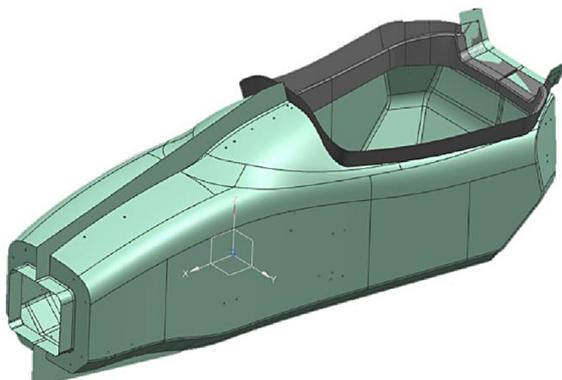


Figure 2. Assembly of three-piece molding system

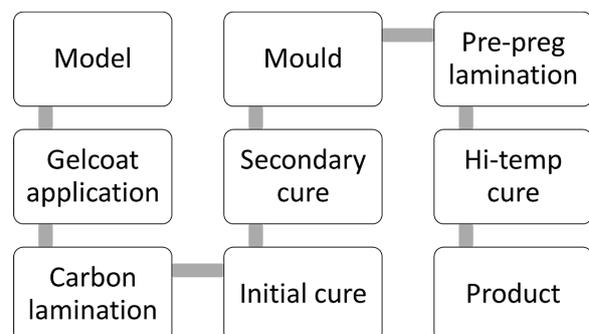


Figure 3. Scheme of manufacturing process of monocoque

Gelcoat

To create a gelcoat, one requires a laminating resin mixed with short life hardener. The chosen system was laminating resin LH 385 together with H 285 hardener. Full properties and data can be found at It has the similar properties as LH 285, yet comes without certification required in aerospace sector, which is not necessary for mould manufacturing. The shape of the mould which has many vertical surfaces requires the gelcoat to remain at vertical surfaces, without external forces applied (only its own weight). This type of physical property is called thixotropy and can be achieved with adding aerosil to the mixture. Additionally, to decrease chance of cracks, the titanium oxide will be added as well as red pigment to enable for easier recognition of uncovered areas, as the white colour of model and the transparency of resin system could make it prone to overlooks during gelcoat coverage. The exact mixing ratios were established by sample tests and guidance from academic staff. The ratios are stored in Table 1.

Laminating the moulds

This was depicted at figure below. The process started with inserting 5mm aluminium positioning pins into the holes machined in the models. Their purpose is to transition position of the attachment points from model to the mold. All pins were covered with release agent and the fitting space between model and a pin was sealed by applying extra layer of solid release agent.

Next models were covered with a 400 gsm layer of gelcoat (Figure 4a–d) and were left for about 2 h in order for the gelcoat to enter the gel state. When it did, a subsequent layer of gelcoat was applied and again left for the same amount of time. A total of three layers of gelcoat were applied. When the last layer entered the gel state, the models were covered with layers of carbon fiber, which would create the mould structure. First with a thin layer of 160 gsm twill fabric was applied (Figure 4e) followed by a layer of a thicker 200 gsm biaxial fabric reinforcement (Figure 4f). In the places where the studs are located the layup was additionally

reinforced by the Airrex 80.55 5mm thick foam. Then the layup was symmetrically mirrored for a total of 6 plies. Figure 4 g-l presents the bagging process where first the peel-ply was applied followed by foil and breather. In the end the bag was sealed and connected to vacuum pump for the curing process, which took 24h. The process was repeated for all three pieces of mould assembly.

Mould cure

One of the biggest challenges of manufacturing process was to increase the glass transition temperature of the epoxy resin used in the mold to approximately 90–100 °C as it had to be resistant to temperatures used during low temp curing of pre-pregs. According to the TDS of LH 385 the glass temperature of epoxy resin equals to the cure temperature increased by 30 °C. Therefore, for molds cured at room temperature it can be assumed that their temperature resistance is about 50 °C. If the desired temperature resistance (90–100) was to be reached, the moulds would have to be cured at around 70 C. However, glass temperature of used PU models was equal to 47 °C. There was no possibility of reaching the required temperature for OOA pre-pregs at one cure cycle as curing at higher temperatures could change the geometry of the molds and model as they would become un-solidified when entering glass transition state. Due to that reason other solution had to be implemented.

After the first cycle has been completed, the part was naturally cooled down and separated from the model. Secondly, the mold has been placed in an oven and subjected to next annealing cycle (Figure 5). This time the temperature was gradually increased to 75 °C with the same temperature step and ramp rate. When reaching the maximum temperature, the mold had been left for 3 hours at that condition and ultimately, it was naturally cooled to room temperature.

Monocoque molds joining

After the mold and model separation, the pieces were joined together first with clamps and micro-positioned to obtain best match possible. To connect the molds, several holes were drilled

Table 1. Gelcoat mixing ratios

Ingredient	LH 385	Titanium oxide	Aerosil	Pigment	H 285
% mass	66.5	1	3.5	1	28



Figure 4. Mold manufacturing process

in the flange, after the halves were positioned accurately. Joined molds had been annealed in horizontal orientation. Prior to the process, pins were inserted into the structure (Figure 6) as there was a concern about possible deformation of positioning holes. Afterwards the surface of the molds had been thoroughly cleaned with acetone and prepared for Frekote Mold

Sealer application. The challenge was to seal any remaining dips at joining lines of the mold, which result from presence of blends at edges instead of sharp corners due to model machining process limitation. An Airtech Toolwright 3 film had been used as its thickness ($75\ \mu\text{m}$) will most likely be neglectable when it comes to geometrical aspects.

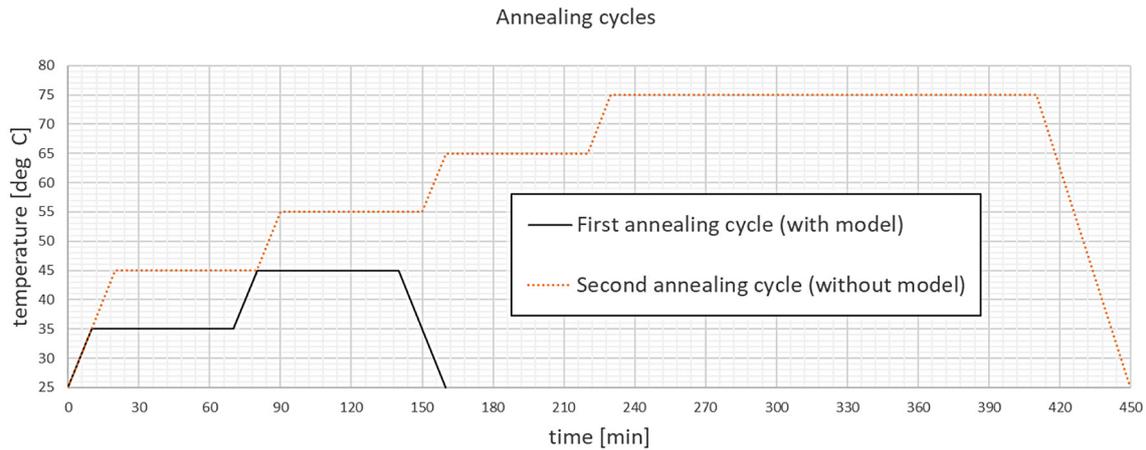


Figure 5. First and second annealing cycle

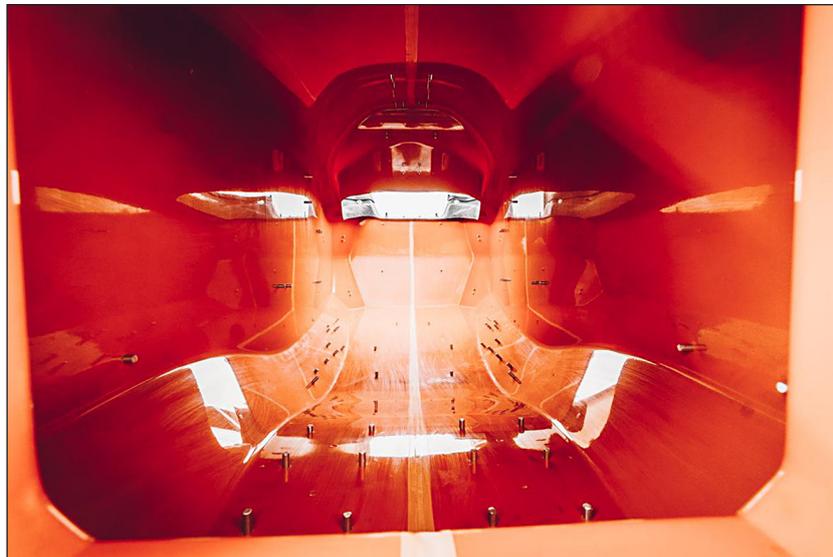


Figure 6. Inside of a mould viewed from the front

Laminating inside layer

As the layup has been verified by the real-life testing beforehand it had to be replicated in primary structure. It consisted of the following layers of pre-preg: $[45_{200}^{\circ}, 45_{200}^{\circ}, 90_{200}^{\circ}, 45_{400}^{\circ}, 90_{400}^{\circ}, 45_{200}^{\circ}]_T$. As it can be seen the reinforcing layers of 400 gsm fabrics were placed inside the layup, with lighter cloths on the surface. The first layer (Figure 7) had been debulked under the vacuum bag with high-perforage release film in order to allow the fabric to fit into sharp corners and enhance the surface of the product. Consequently, next layers were laid on top of each other. The fabric flat patterns used during lay-up accounted for lap joining of the following layers, yet they didn't add unnecessary material. Pins were used to create through holes in a product. They were

inserted after the layers of carbon had been laid, as it made the process easier. Following the successful lay-up of all layers, the harness mount foams were added to the structure with one layer of adhesive release film. They will enable to position the harness mount inserts properly. Next, the peelply was laid together with perforated release film and breather that has been present on both sides of the structure, as there was a concern whether the mould surface contains small sharp bits of carbon fibre, that could damage the vacuum bag.

Core and inserts

The general idea of insert geometry in this monocoque has been based on [3] and consist of aluminum bushing between the carbon skins with or without the filled core of aluminum honeycomb

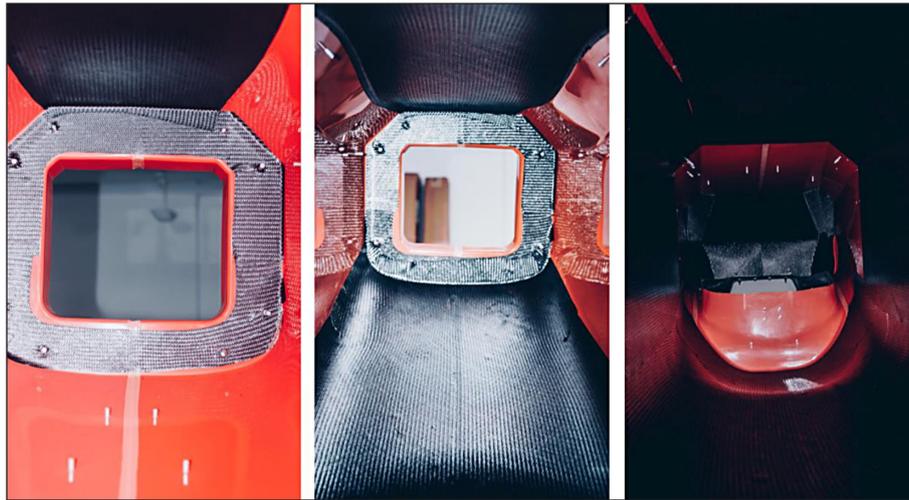


Figure 7. First layer of pre-preg fabric laid on a mold

(Figure 8a). The inside diameter of aluminum bushing was set as a tight clearance hole for M6 and M8 screws. Their outside diameter has been set accordingly to expected loads and were computed based on [3]. For the higher loads exhibited by some components, the honeycomb had to be filled to additionally stiffen the area around the insert. Such areas included mainly the suspension system mounting points for which epoxy filled honeycomb panels were prepared (Figure 8b). In the next step aluminium bushings were inserted into these panels and glued (Figure 8c). The white color of panels comes from an epoxy filler i.e. microballoons (6014 type). They have been mixed in the mass ratio of 10:3 to obtain lightest epoxy

possible. Raw panels were post cured at 80°C to prevent clogging of CNC milling machine as this his increased their hardness. Moreover, the aluminum bushings were made using lathe machine and their surface had been prepared for gluing by grinding it with low-grade sand paper. Next, all the surfaces had been cleaned with acetone and glued to each other using 2 component epoxy glue (Loctite 9466). When the glue had cured at room temperature, both faces of panels were grinded with the same sand paper to obtain both good adhesion surface and remove any additional glue that has leaked. Ultimately machined pieces were glued to the CFRP skins (Figure 8d). Their positioning was realized with shoulder bolts (ISO

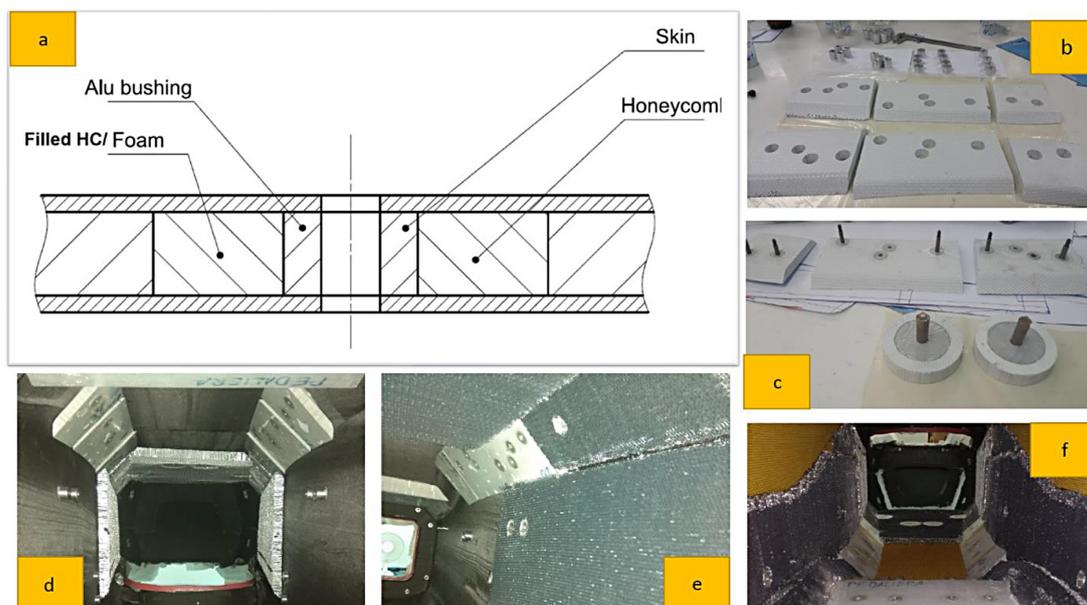


Figure 8. Mounting points (inserts) preparation process

7379) wrapped in thin masking tape to prevent glue adhesion (Figure 8c). Other bushing which didn't require reinforcement from filled honeycomb panels were glued to the skins first and then sheets of honeycomb with pre-drilled holes were placed around the bushings (Figure 8e). As multiple thicknesses of honeycomb were used, it had to be chamfered at the boundaries to provide smooth transition. It can be seen at Figure 8 f.

Final layer

After curing the core with inserts the inside layer of carbon plies were laid forming the inside skin of a monocoque. Again, same procedure followed with debulking of first ply and mirroring the layup so that it is now $[45_{200}, 90_{400}, 45_{400}, 90_{200}, 45_{200}, 45_{200}]_T$. This time however, the pins were not inserted as the position of inserts was already established. This meant that the fabrics would not be pierced through, and holes would have to be drilled after the final cure. When the cycle has finished the product was extracted from the moulds. There were some visible markings from the release agent used, and occasional pinholes, thus it was necessary to gelcoat the surface (Figure 9).

RESULTS

To sum up the manufacturing process a comparison of costs will be made between the investigated approach and some of the typical manufacturing processes for monocoques of this type. The standard (reference) manufacturing technology solution is the one where epoxy tooling boards which are CNC machined to obtain models. Next molds are



Figure 9. Final product after extraction from the molds

laminated on the models using tooling pre-preg and cured. Finally, the product is made using such molds in the same way as depicted in this case study.

Other approach is so called cut and fold method, which consists of first laminating the flat panels and later removing the strips of material at places where the bends are necessary. Next, panels are bended to the desired shape and reinforcements are added at the bend locations. Usually, the honeycomb is filled with epoxy at the bend radius to stiffen the structure. Yet another approach is to mix the two solutions and apply the so called “hybrid” method where the molding system is created from CNC laser cut sheets of aluminum, which are bent to the desired shape. Next, they are positioned to create the interior of a mold. This approach was used in [20] together with hardpoints / insert locating holes cut in the aluminum sheets. It has the advantage of skipping the mold making procedure, yet the aluminum sheets are heavier and also have higher coefficient of thermal expansion. Also, it is slightly less accurate than the standard molding process as it was noticed by the authors. The cost of each type of process has been presented in Table 2. It has been calculated excluding labor costs as they are dependent on region, thus only the material and processing costs were presented. The materials cost also includes all auxiliary materials that had been used e.g. vacuum bags etc. The sub costs were calculated relative as a percentage of a total cost as the values itself are not very meaningful when it comes to other projects. The total cost is a sum of three components – models, molds and product.

As it can be seen the standard manufacturing process is the most expensive as the material cost of creating the models is relatively high. This simulated cost of standard process is close to the one in [19] where the cost of manufacturing was about 10 250 USD. Although the structure there consisted of also the rear part thus making it a full monocoque. The important information to be taken from the cost simulation is that the product costs are not dominant of majority of solutions.

DISCUSSION AND CONCLUSIONS

The manufacturing process used to produce the monocoque using the alternative method can be successfully used instead of the standard approach. It has both advantages and disadvantages. On the plus side it can be said that it is

Table 2. Simulation of costs for different manufacturing processes

Total [USD]	Standard	Alternative	Cut and fold	Hybrid
	11447	5815	5371	5028
Models	61%	16%	0%	0%
Materials	51%	5%	0%	0%
Processing	11%	26%	0%	0%
Molds	14%	20%	0%	44%
Materials	11%	8%	0%	24%
Processing	3%	13%	0%	20%
Product	25%	49%	100%	56%
Materials	17%	33%	65%	38%
Processing	8%	15%	35%	18%

significantly cheaper than the standard solution and only slightly more expensive than the other methods such as cut and fold or hybrid. The downside is that it requires more post cure cycles and the temperature window allows for only the low temp cure of the pre-preg material.

The solution could be further improved by using different polyethene (PU) molding paste, which has higher glass transition temperature, to create the models. This would limit the number of post cure cycles of the molds to one as well as increase the temperature at which the mould can be effectively used, thus enabling the high temperature cure of epoxy pre-pregs. Obviously, such process would have to be verified by performing a similar case study as the Styrofoam used for the process could be used at high temperatures. The cut and fold solution is obviously cheaper, however the disadvantages of such process (accuracy and design freedom) usually mean that the solution cannot be used as it was the case in this project.

Considering the other aspects of manufacturing process, the molding system could have been improved by machining holes in the models, which would serve as positioning holes for joining the two halves of a mold and the cockpit opening together. In this project positioning was done using the existing symmetrical insert holes, yet it could be changed to separate positioning holes on the mold flanges.

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