

Reducing Defects in Composite Monocoque Frames

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Along with the development of new structural materials, the study of novel manufacturing techniques becomes necessary to improve their performance and achieve optimal mechanical resistance thresholds. The present paper deals with the expedients and precautions necessary to avoid the formation of defects on carbon fiber reinforced polymers manufactured over a high-density polyurethane (PU) foam pattern. Particularly, for the attainment of a defect-free monocoque structure for an innovative solar vehicle. The experimental campaign carried is hereby described where foam pre-treatment steps were thoroughly explored in terms of sanding and application of chemicals such as release agents and sealer. Overcoming the inherent challenge of using a yet undiffused and little-known pattern material, successful results have been attained.

Keywords: Solar vehicle, monocoque, carbon fiber-reinforced polymer, pre-treatment, autoclave.

1. INTRODUCTION

The preferential use of composite materials, mostly carbon fiber-reinforced plastics (CFRPs), is a reality nowadays in all mobility-linked industries, such as aeronautical [1], marine [2], and naturally, automotive [3-5], due to the reliable mechanics and low density of these materials. Given the forefront role played by composites in structural design, the domain of manufacturing techniques that yield materials with the best possible quality is essential to ensure the performance and safety of vehicles.

Inside the process that leads to the realization of CFRP components for automotive applications, high-density foams, predominantly epoxy, are often used because of their high-temperature resistance (up to 260°C) and good endurance properties [6]. The fabrication of patterns is an essential step in the manufacture of light and highly performing vehicles [7,8,9] given that they are partially responsible for determining important part features such as dimensional tolerances, effective curing process and surface finish.

This aspect is particularly pertinent in the case of solar-powered electric cars, where the energy efficiency represents the base for the whole functionality and usability of the vehicle [10]. For this application, a *zero defects* approach in quality production would permit to fully benefit of the design optimization toward the highest performance of the vehicle [11-13].

De Camargo et al. [14] showed that designing wheel hubs with carbon fiber would save approximately 1% of the battery capacity of a solar-powered car, achieving a fair safety factor of 85% of that if aluminum was used instead. In another research [15] comparing three types

of wheel hub to integrate the suspension system of different categories of solar terrestrial vehicles, carbon fiber demonstrated superiority by having a sufficient safety factor while bearing half of the weight that aluminum would in all wheel hub designs.

In order to guarantee this advantageous application of carbon fiber reinforced plastics safely, the conduction of optimal manufacturing practices is crucial to avoid unexpected laminate failures [16] that could be originated by inadequate curing or handling of material. For instance, the cure cycle has an acute effect over the spring-in of laminates [17], which might unchain undesirable stress concentration regions in the part during operational conditions and potentially lead to failure when external influences forces [18-20] take place.

Hence, taking into account an ineffective first approach on handling PU for manufacturing reduced scale models of solar vehicle parts where the pattern was wasted due to the incomplete catalysis of the laminate (Figure 1), further investigations became necessary.

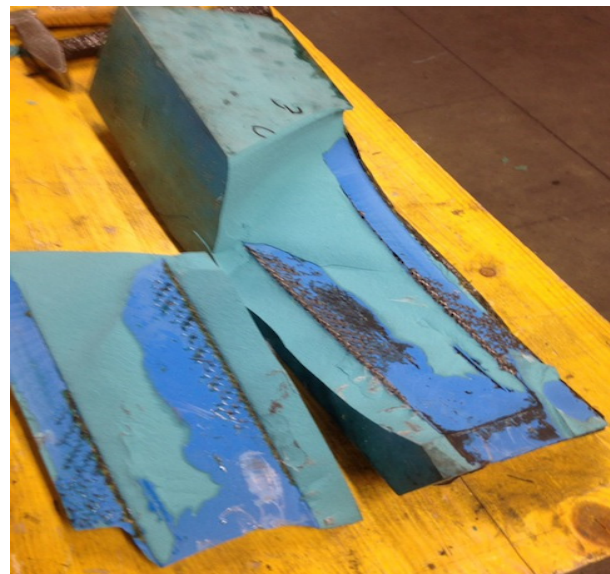


Figure 1. Example of non-catalysed model

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2. MATERIALS AND METHODS

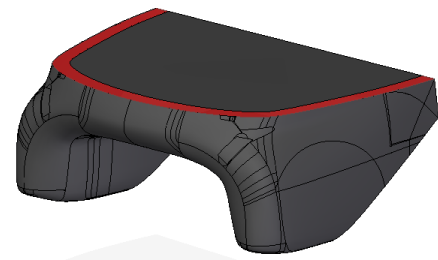
The pattern material was the first variable to be analyzed given that it is a recently developed product. Experiments were conducted in lab aiming to figure out the issue regarding to the unsuccessful cure portrayed in Figure 1 and improve the production process. The method chosen was based on designing diverse surface pre-treatments for this not perfectly known material, perform the cure of a specimen, and analyze its outcome quality.

Hence, the objective was to achieve a laminate that detaches successfully from the pattern, presenting an adequate roughness in order to provide a good surface finish of the final part that would be made using this primary laminate as mold. An example of this production process is depicted in Figure 2, which regards the manufacture steps of the monocoque:

- CAD design of the geometry (A);
- Manufacture of polyurethane pattern by milling and polishing agglomerate blocks (B);
- Production of the carbon fiber mold from the pattern (C);
- Lamination of the monocoque chassis on the carbon fiber mold (D).

With the aim of granting a wide analysis, a considerable number of variables was tested to comprehend whether they play or not an important role on the carbon fiber mold manufacturing over a polyurethane pattern. Setting the carbon fiber mold material as a fixed material, the tested variables can be summarized in pattern material and type of release agent; where the presence of release agent, sealer, wax and their methodology of application varied as well. The materials used in this assessment are detailed in Table 1.

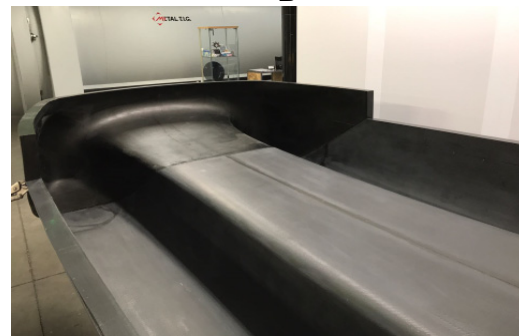
Independently of the usage or not of part of the pre-treatment materials described to vary the test parameters, the order was always the same: varnish application on the mold, cure, sand-paper, sealer, release agent, wax, composite assembly and final cure. The varnish mixture was proportionally composed by the ratio of 100g of varnish, 20g of hardener and 10g of acetone, as indicated by the supplier. After the utilization of this mixture in a certain number of coatings, independently of the application method of the product, all polyurethane samples were cured overnight at 80 °C for 10h. The cure time between each coat of sealer, release agent and wax was 30 minutes.



A



B



C



D

Figure 2. Monocoque realization steps: CAD design (A), pattern manufacture (B), mold production (C) and monocoque lamination (D).

Table 1. Main materials used in the experiment

Material	Form	Technical Details	Supplier	Usage
Polyurethane	Foam in blocks	Blue Corintho H700	Duna Corradini	Pattern production
Carbon composite	Pre-impregnated	200 and 630 Twill	Impregnatex	Mold production
Epoxy	Resin	Blue Sea 125	Duna Corradini	Varnish & sealer
Epoxy	Resin	Dunapox H156	Duna Corradini	Varnish hardener
Polymers mix	Resin	Flex 5.0	Zyvax	Release agent
Polymers mix	Resin	Frekote 770 NC	Loctite	Release agent
Polymers mix	Resin	Sealer GP	Zyvax	Sealer
Wax	Paste	FR16	Mates	Realease agent

The laminate assembling was made with 4 plies of *twill weave* carbon fiber pre-impregnated with epoxy accounting for 200g/m² of surface density for the first layer and 630g/m² for the others (this parameter is measured by the manufacturer without the resin; after catalysis, the weight increases about 40%) under a [0/90]₂ orientation. The samples were later submitted to a vacuum bag compression process, and then placed in the autoclave where the curing process succeeded. Figure 3 exhibits an example of ply assembly and cure preparation.

2.1 Varnish application

The majority of patterns were covered spraying the varnish solution in 3 layers with 2-hour cure time between each treatment. Given the potentially thick layer of varnish generated, the application of the product with paper-towel in 2 layers was made in a couple of samples, with a cure time defined by a test in which paper-towel was rubbed against the surface and nothing came off.

2.2 Pattern material

Besides PU, a steel plate was also used as pattern for the carbon fiber specimens to check the degree of influence of the PU, once previous works were developed using steel and yielding perfect results. Thus, a good standard parameter for comparison. After all, the main concern about using PU is that, although it has elevated density, it might be porous enough to release gas during cure.

2.3 Process parameters

Using a total amount of 18 specimens, characterized according to Table 2, the variability in the process quality was investigated in respect to the following 7 aspects, mainly related to the pre-treatment:

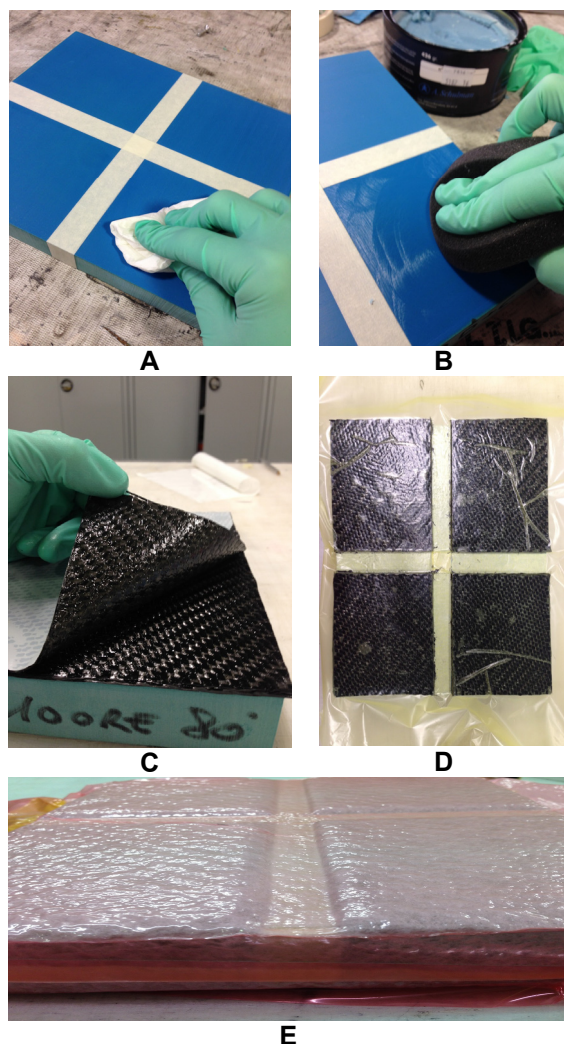


Figure 3. Production steps: release agent and sealer application with paper-towel (A); wax application with a sponge (B); ply assembly (C); vacuum bagging for autoclave cure (D) and after cure (E).

Table 2. Classification of manufacturing variables under investigation.

Step	Treatment	Specimen																				
A	Mold	Steel																				
		Polyurethane																				
B	Varnish application	Paper-towel																				
		Spray																				
C	Sand-paper granulometry	Not used																				
		400																				
		220 - 400 - 4000 dry																				
		220 - 400 - 4000 moist																				
		220 - 400 - 6000 dry																				
	220 - 400 - 6000 moist																					
D	Sealer																					
E	Release agent (<i>Flex</i>)																					
F	Release agent (<i>Frekote</i>)																					
G	Wax coating																					
H	Conditioned carbon fiber																					

- Pattern material: PU or steel;
- Method of varnish application: spray or paper-towel;
- Presence of release agent, sealer and wax;
- Type of release agent: *Flex 5.0* or *Frekote 770 NC*;
- Types of sand-paper used: with 220, 400, 4000, 6000 granulometries and their combination;
- Wetting the sand-paper with the finest granulometry;
- Pre-conditioning of carbon fiber.

Finally, the coupons were submitted to an autoclave curing of 10 hours at 80°C, as recommended by the PU and carbon fiber suppliers.

3. RESULTS AND DISCUSSION

The present analysis showed outcome flaws for every coupon, even if the severity was not uniform. Figure 4 displays the most prominent defects found in the samples, which varied from inability to release breaking the pattern, to porosity concentrated in specific spots and even surface cracks.

A visual analysis permits to infer that the defects in all samples are very similar, identified by voids on the surface cured in contact with the mold, characterizing regions in which the resin was not properly catalyzed. None of the variables association presented an acceptable outcome regarding the surface finish of the specimens. They all presented voids and some resin always remained attached to the pattern (be it from polyurethane or aluminum, hence excluding the hypothesis of the problem being derivate from the mold material).

This assessment leads to the conclusion that not enough attention was given to the carbon fiber itself. Although the most suspicious material was PU for its yet rare usage to manufacture fiber reinforced composites, carbon presented a behavior that indicated either an inadequate cure cycle not suitable to the impregnated resin, or poor handling/storage.

After the experiments above, a TGA analysis (as in [21,22]) actually showed that this specific resin pre-impregnated on the carbon needs a temperature hold of approximately 1 hour at 50°C so the catalysis can be complete. Otherwise, the formation of bubbles due to reticulated resin was present, because the solvent from the resin would not evaporate without the 50 °C hold. The reason for this behavior of the resin was not clear if it was intrinsic or the resin had suffered some deterioration in a certain level before submitting it to autoclave cure. A distortion on its performance has become an actual possibility supported by Figure 4E that shows excessive resin overflow in the borders of the composite plate while the flaw in its center is characterized by lack of resin, indicating that it was not able to penetrate through the plies.

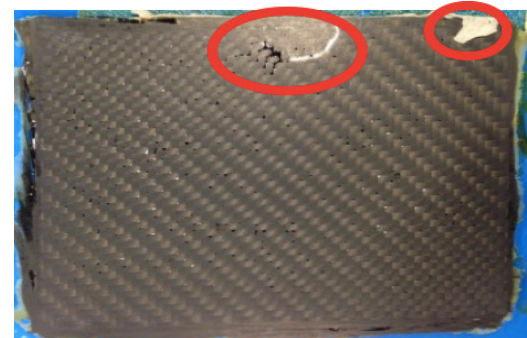
Hence, the technical solution is based on a simple adaptation of the thermal cycle, not depending on any of the other variables, but naturally keeping the standard manufacturing procedures of applying varnish, release agent and sealer. Thus, as practical outcome, it was possible to unlock the criticality moving from the design phase to the production phase toward the realization of the solar car.



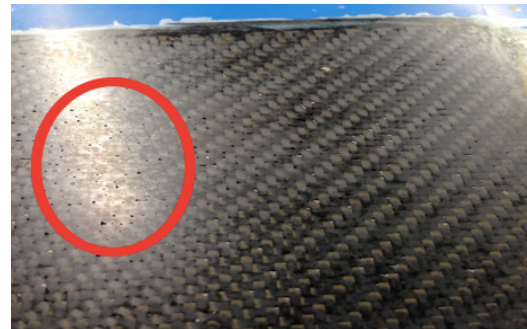
A



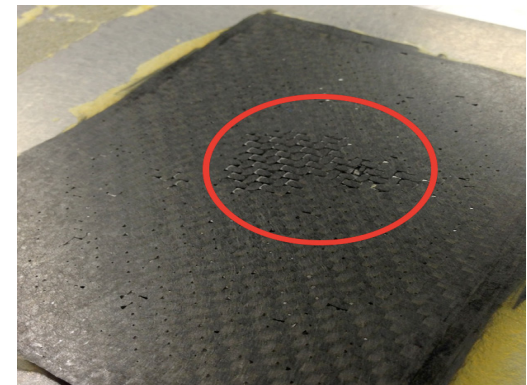
B



C



D



E

Figure 4. Defects found in the specimens: from incomplete detachment from the pattern (A,B) or local cracks (C,D) to accentuated surface irregularities and voids (E).

4. CONCLUSION

A thorough analysis on a pre-treatment-based methodology for solving a manufacture problem of autoclave cure of low-temperature-cure pre-impregnated carbon fiber laminated on a high-density polyurethane foam pattern. Experiments varying parameters such as varnish, release agent, sealer, release wax, sanding, pre-conditioning of the carbon fiber and even a second pattern material were carried. The results were initially inconclusive given that all coupons presented flaws originated by deficient resin cure.

Once the insufficiently good results show that neither the products used on pre-treatment (as well as their order, number of applications, or manufacturer) nor the mold material (polyurethane or aluminum) are fully responsible for the void defects, the incomplete resin catalysis has been therefore attributed to the carbon itself and its thermal cycle.

Consulting the data provided by the suppliers is not always enough to ensure the most adequate usage of materials, particularly chemicals (e.g. resins). Thus, the assessment of all manufacturing steps performed through small-scale experiments, such as the one described in the present work, are advised to be performed indistinguishably before the practical step of any construction projects, specifically those involving structural materials to secure the realization of reliable end-products.

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**СМАЊЕЊЕ ДЕФЕКТА У КОМПОЗИТНИМ
ОКВИРИМА ШКОЉКЕ**

К. Фрагаса, Ђ. Минак, М. Сасатели

Поред развоја нових структурних материјала, развој нове технике производње како би се побољшале њихове перформансе и постигли оптимални прагови механичке отпорности. Садашњи рад се бави потребама и мерама предострожности које су неопходне како би се избегло формирање дефеката на полимере ојачаним угљеничним влакнима произведеним путем полиуретана (ПУ) високе густине. Нарочито, за реализацију шкољке иновативног соларног возила. Описана експериментална кампања описује се тамо где су претретирани пене детаљно истражене у смислу брушења и примене хемикалија као што су средства за отпуштање и заптивачи. Превазилажење инерентног изазова коришћења још неуједначеног и слабо познатог материјала узорака, постигнути су успешни резултати.