Manufacturing Challenges for Custom Made Solar Vehicles in South Africa

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Abstract
Solar challenges are designed to test the reliability and efficiency of solar powered vehicles in endurance races. In the past these manufactured vehicles were technology drivers and led to advances in electric motors and solar cell efficiency. The speed in relation to power consumption is one of the main design considerations, with the only energy source being solar power. In the design and manufacturing of these vehicles a number of requirements need to be met in order to pass the safety standards. The Sasol Solar Challenge (SSC) created an opportunity for South African universities to design and manufacture custom made solar powered vehicles. This paper explores and discusses the challenges for manufacturing solar vehicles in South Africa. Key elements like the communication gap between design and manufacturing, the cost of lightweight solar encapsulation, the shortage of local suppliers and expertise in composite manufacturing are evaluated. These insights can be used as foundation for strategic decisions by future stakeholders.

Keywords
Composite Material, Solar Encapsulation, Concurrent Engineering

1 INTRODUCTION

Manufacturing of products and goods is probably the most important economic activity in the world. It is the backbone of modern industrialized society as it always has been cornerstone of the world's economy. Having a strong manufacturing base is important to any society or community, because it stimulates all the other sectors of the economy [1]. In the manufacturing of solar vehicles, with design trends towards higher strength-to-weight ratios and energy efficiencies, more stringent tolerances are required, which in turn challenges the manufacturing operations [2]. The importance of the manufacturing sector for growth and prosperity has always been high and is even increasing as innovation cycles are becoming shorter and the interdependencies between different developments are becoming more pronounced [3]. Figure 1 illustrates the megatrends of our time [4]. This figure illustrates the future challenges and the solutions we envisage.

Figure 1 - Megatrends of our time – What does the future hold? (Adapted from [4])

In order to develop comprehensive technologies, that will enable the creation of novel product features in terms of efficiency and added value, the complete value chain within the manufacturing of solar vehicles has to be regarded [4]. Advanced manufacturing technologies can contribute to higher efficiency along the whole value co-creation chain [5] and increase the eco-efficiency of the vehicle. The SSC created an opportunity for South African universities to design these solar powered vehicles in a concurrent engineering (multi-disciplinary team) [6] environment. This research paper highlights a number of critical manufacturing and engineering competences developed in the course of the team's preparation to participate in this race. The project proved to be a platform to promote engineering and technology careers, to engage with industry and to attract students towards pursuing postgraduate studies. Composite materials were used extensively in this vehicle as their higher strength and stiffness (properties per unit weight), when compared to metals, offered interesting opportunities during the design phase. However, being nonhomogeneous, anisotropic and reinforced by very abrasive components, these materials are difficult to machine [7]. Although, the use of composite materials in manufacturing is a well-established technology around the world [8], the expensive tooling and the long processing time (including curing) were actual obstacles. The solar car also required a monitoring system that can capture and display information about the state of the vehicle. Printed Circuit Boards (PCB) were manufactured using laser cutting technology to mechanically support and electrically connect electronic components using conductive pathways etched from copper sheets laminated onto a non-conductive substrate. The team also realized that the current situation in the tooling industry is characterized by high competition on the market, as mentioned by [8]. In this study advanced manufacturing processes such as composite manufacturing, the mould making process, solar encapsulation and PCB manufacturing were discussed and evaluated. The concurrent engineering framework is illustrated and the design challenges mentioned.

2 DESIGN REQUIREMENTS AND APPROACH

In the design phase of this solar vehicle, it was critical to consider what the stakeholders desire according to the requirements [9, 10], that the design was technically and organisationally feasible; and that the manufacturing processes were financially viable with the limited sponsorships. This vehicle was designed to participate in long distance races (5100 km around South Africa). It was not possible to outsource design as engineering designs have to be modified constantly to match the technology or manufacturing capabilities. The team was initially left with the dilemma of how to communicate their capabilities to their designers and vice versa. Using design for manufacturing (DFM) tools that presents all manufacturing capabilities on-site and applying design for assembly (DFA) principles [11], it was possible to produce parts that are relatively easy to manufacture and assemble given the constraints. The team used a systematic concurrent engineering framework [6], illustrated in Figure 2, to bridge the communication gap between the different consortium members.

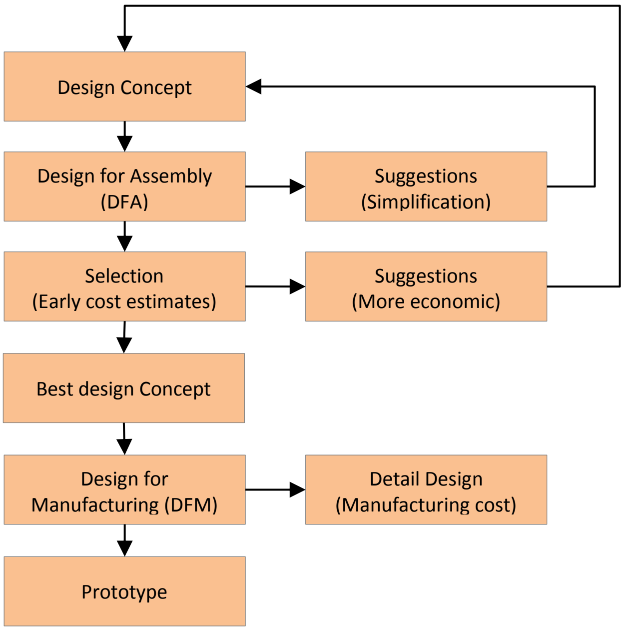

Figure 2 - Framework used for the systematic design phases (Adapted from [6])

The DFM challenges were found to be at the design intersection between what is technically and organisationally feasible and what is financially viable. The render of the final detailed design is shown in Figure 3. Understanding DFM was paramount, especially when design requirements exceed technology or manufacturing capability.

Figure 3 - Render by the Industrial Design department (FADA) of the detailed design of the Solar vehicle (Ilanga 1)

Applying the principles for DFA [11], it was possible to reduce the number of parts and movements. It also helped to design for alignment and to avoid visual obstructions and multiple fixings on the solar vehicle.

3 ADVANCED MANUFACTURING (AM) PROCESSES

AM makes use of innovative manufacturing technologies and software integrated with a skilled workforce in a production system capable of manufacturing a heterogeneous mix of products with both the efficiency and flexibility of custom manufacturing in order to respond quickly to customer demands. The following processes were found to be challenging during this project.

3.1 Manufacturing moulds for body panels

In order to manufacture the body panels of the solar vehicle, a mould was needed. These moulds can be manufactured by creating a negative directly according to the shape from which the body panel can be pulled; or by manufacturing a plug (positive) that in is used to pull the mould (final female), which is then used to make the actual body panel. Due to the machinability challenges, size constraints and costs of the materials, it was decided to cut the plugs from polystyrene, rather than creating a negative directly from a more rigid (tougher), but more expensive material. CAD models were created for each panel of the body and then each of the split panels or split lines for the mould was CNC milled as shown in Figure 4. The plugs were then covered in fibber class and used to pull the moulds from. When designing the plugs it was critical to consider the size of the mould and the CNC machine bed. A cutting strategy had to be developed according to the work piece material and cutting parameters. The undercuts in panels and split lines of the mould was also considered. Creating a direct positive mould would have made it logistically challenging, as the mould would have been too large and heavy. This strategy of manufacturing the plugs first was found to be a very accurate method; and the removal of the final mould from the plugs was relatively easy.

Figure 4 - CNC milling of the polystyrene plugs for the moulds of the body panels of the solar vehicle

Each panel was closely evaluated and tested by using scaled (Scale 1:5 and 1:10) male plug prototypes as shown in Figure 5. This helped to plan the manufacturing steps of the plugs and to evaluate the aerodynamics of the body using FEM modelling. The polystyrene was also initially tested to see if it can be used as a material to machine the plugs out of.

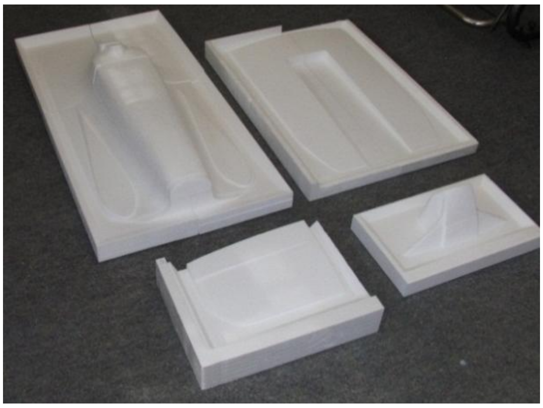

Figure 5 - Positive (male plug) prototype made of polystyrene (Scale 1:5) from the milling operation

The material was found to be dense enough to use the CNC mill's cutters. Testing was done using different types of glues to assemble the blocks. The strength of the polystyrene was tested under a vacuum to see if it can be used without any outer hardened shell. It was found that under a vacuum (1bar) the polystyrene collapsed in small sections. Thereafter, different material pastes were evaluated. The idea was to mill the plugs at an offset smaller than the actual size out of the polystyrene, add a paste, let it harden and mill it again. After various tests with the paste, it was decided not to use this method, since it is difficult to spread evenly and impossible to exclude internal air bubbles. Another challenge was time, since the parts would need to be manufactured again. Thereby, it was concluded that an outer hardened shell will be the best solution for this challenge. In order to create this hardened shell the milled polystyrene was covered with a thin layer of composite material and then sanded to the desired smooth surface.

3.2 Composite Materials

Composite materials are formed from two or more materials producing properties that could not be obtained from any one material [7]. One of the constituent materials acts as the matrix and at least one other constituent material acts as the reinforcement in the composite. Composite materials can be classified on the basis of the matrix material used for their fabrication:

- polymer matrix composites (PMC)
- metal matrix composites (MMC)
- ceramic matrix composites (CMC)

Theoretically, a multitude of materials can come under these categories. In this case, PMC are referred to as fibre reinforced plastics (FRP). Glass fibre reinforced plastics (GFRP) are by far the most commonly used materials in view of their high specific mechanical properties and low cost. GFRP was used in this project.

3.2.1 Vacuum bag moulding of GFRP composites

Vacuum bag moulding was used to cure the hardened shell of the final aerodynamic body shell. This process is an extension of the wet lay-up process, where pressure is applied to the laminate once laid-up in order to improve its consolidation. This was achieved by sealing a plastic film over the wet laid-up laminate and onto the tool as shown in figure 6. The air under the bag was extracted with a vacuum pump. Thus up to one atmosphere of pressure could be applied to consolidate it. The benefit from this process was that higher fibre content laminates could be achieved compared to standard wet lay-up methods. It also helped to reduce the void contents compared to normal wet lay-up methods.

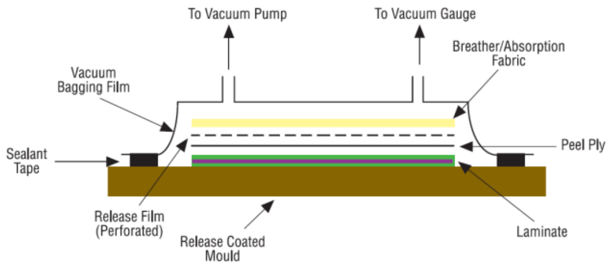

Figure 6 - The whole solar vehicle mould was put into a vacuum bag for the moulding of composites

The wet lay-up adds to the cost both with labour and disposable bagging material expenses. A higher level of skill was required from the group of students as shown in figure 7. The vacuum bag was a bag made of strong rubber-coated fabric used to laminate the composite materials. The open end was sealed and the air is drawn out of the bag through a nipple using the vacuum pump.

Figure 7 - Wet lay-up of composite material for final aerodynamic shell, before placed under vacuum for curing

The most economical way was to use a vacuum pump. As a result, uniform pressure approaching one atmosphere is applied to the surfaces of the object inside the bag, holding parts together while the adhesive cures.

3.2.2 Machining of composite materials

Machining of composite materials differs significantly in many aspects from machining of conventional metals and their alloys [12, 13]. Investigations carried out in [14] of FRP composites with different fibre orientations allowed for the clarification of the cutting mechanisms taking place in FRP.

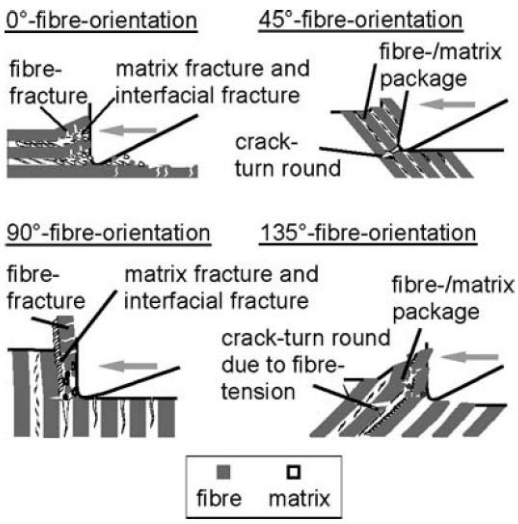

Figure 8 - Cutting mechanisms for FRP composites [14]

Machining of composite materials also still require a better understanding of cutting processes with regards to accuracy and efficiency. Even with this near-net shape process, there was still a need for secondary machining to the required accuracy. Machining composites can produce more damage than desired, if not done carefully. Therefore, it was critical to keep the cutting tools sharpened and to select the cutting parameters appropriately. The hardness of the glass and more especially, of the carbon fibres results in a high rate of tool wear [7]. The team also realised that an increase in tool life can lead to (almost 9%) cost reduction, while an increase in cutting parameters can lead to a reduction in machining costs (up to 18%) [14].

3.3 Encapsulation of solar cells (ESC)

A competitive solar vehicle needs around six square meters of solar cells that produce approximately one kilowatt of power. This equates to 514 monocrystalline cubic zirconia silicon wafers (16.8% efficient) coated in clear glass (total thickness ±0.15 mm) cells as illustrated in figure 9. The manufacturing challenge was to protect these cells from the terrestrial elements over a prolonged period of time. Typical cell encapsulation is to frame these cells in glass, sealed in EVA (Ethylene-vinyl acetate). The problem is that glass encapsulation is not feasible, mainly due to the vehicle's weight restrictions (total dry weight ≤150 kg).

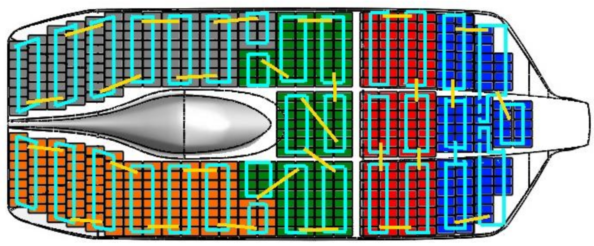

Figure 9 - Cell Layout and wiring on the top of the solar vehicle

During the manufacturing of the solar vehicle the team experimented with composite solar encapsulation, also using the vacuum bag moulding process. Most of the solar cells were hand soldered and encapsulated. The efficiency loss of 3.86% was considered reasonable and the increase in module strength meant the cells could be handled easier and reduced the chance of cell damage significantly.

3.4 Printed Circuit Board (PCB) and other manufacturing processes

A driver information and telemetry system was designed and implemented on the solar vehicle, using PCB boards. The manufacturing challenges were that the design and manufacturing of these boards are only done on a small scale in South Africa (SA). Therefore, PCB etching and printing technologies was required as this manufacturing capability was limited, with larger scale only available abroad. The team used laser cutting technologies to cut the stencil for the PCB. Surface mount components were used to reduce the carbon footprint of the boards, complexity of the assembly and manufacturing costs. The subcomponents were also integrated to reduce the manufacturing costs. Waterjet cutting was used to cut the ribs in the vehicle as illustrated in figure 10.

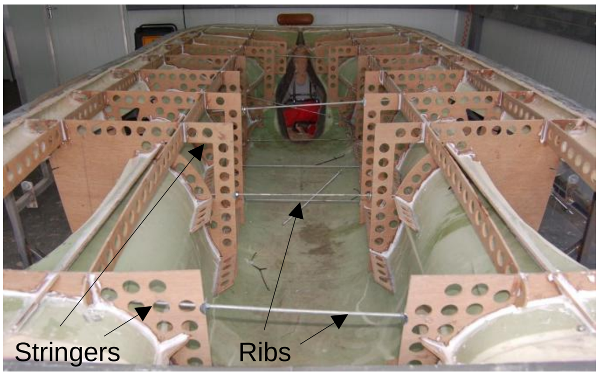

Figure 10 - The ribs and stringers inside the solar vehicle frame of the body

These holes in the ribs helped to reduce the overall weight of the vehicle. The aluminium frame had to be welded by coded welders as shown in figure 11.

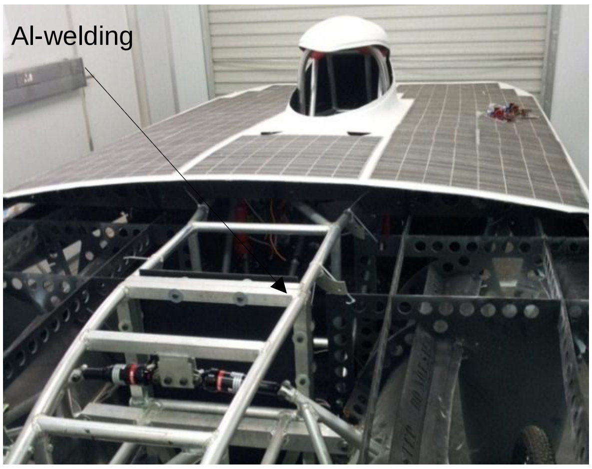

Figure 11 - The Aluminium (Al) frame below the body of the semi-assembled solar vehicle

The Al-welders require a lot of experience and there are only a few capable to weld with a high quality standard in SA.

4 RESULTS AND DISCUSSION

The method of manufacturing the plugs first, when manufacturing the mould for the body of the solar vehicle, was found to be very accurate and the removal of the final mould from the plugs was relatively easy. Encapsulating the solar cells with composite material helped to increase the cells module strength. Thereby the cells could be handled easier and reduced the chance of cell damage drastically. The efficiency loss of the cells (3.86%) was considered reasonable. Applying DFM and DFA principles with a concurrent engineering approach, made it possible to produce the vehicle on time within the budget. The breakdown of the cost incurred is illustrated in figure 12. Although manufacturing took a great percentage of the total cost, it took less time than the design phases.

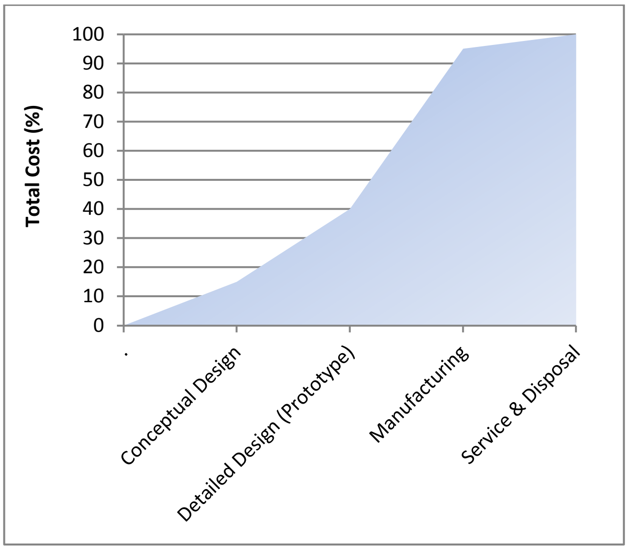

Figure 12 - Cost incurred to fabricate the solar vehicle

It was decided to evaluate the manufacturing processes in terms of proximity, technology, capacity and skills in SA as shown in Table 1. Proximity (Prox) refers to the personal relationships and the knowledge sharing capability. Technology refers to the available technologies for those manufacturing processes, skills to the technical and managerial skills of the helping partner and capacity refers to the selected company's self-sufficiency and volume it can handle.

	Prox.	Tech.	Capacity	Skills
Mould	Very good	Bad	Good	Good
Composites	Bad	Good	Average	Good
ESC	Very bad	Average	Bad	Bad

Table 1 - Evaluation of manufacturing processes of the solar vehicle

The team experienced that during the mould making process it was relatively easy to locate milling workshops, but tough to find a machine that is capable to machine the required size. Composite manufacturing is still very limited and expensive. Although SA's boat building composite artisans are relative skilled, specialised technologies are also required. The majority of these technologies are not locally available and only a very limited number of suppliers could be found. There are very few, if any, lightweight solar encapsulation facilities in SA available. Most of these processes are done in Australia, USA and Germany. The cost of encapsulation of this type can be very expensive. Composites have been used for the solar cell encapsulation (ESC), which require accurate attention during processing, especially with the fragile cells being encapsulated.

5 CONCLUSION

The concurrent engineering framework was effectively implemented within the team to maximise the use of manufacturing technology, while reducing the number of parts to assemble. The manufacturing processes used were discussed and evaluated. The cost incurred to develop the vehicle was illustrated. The vehicle was manufactured on time and within the budget.

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7 BIOGRAPHY

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