COMA '13 International Conference on Competitive Manufacturing

Investigating the Effects of Composite Materials in Solar Cell Encapsulation

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Abstract

In the past few decades our society's increasing demands for energy have naturally resulted in increased utilization of renewable resources such as solar energy. Due to this strong demand the solar car endurance race was established to challenge researchers in this field. A competitive vehicle needs around six square meters of solar cells that produce approximately one kilowatt of power. This equates to 514 monocrystalline silicon half cells. The manufacturing challenge is to protect these cells from the terrestrial elements over a prolonged period of time. In this research study a composite encapsulation method was developed for solar cells and tested. Experiments were conducted to assess the processing of composite materials to improve the mechanical strength of the fragile solar cells. The effects of composites on reinforcement, electrical efficiency and thermal efficiency of the photovoltaic (PV) cells were evaluated. Impact testing to simulate a hailstone shows that the fibreglass sandwich panel structure will protect the surface of the cells, whilst reducing their efficiency by less than 5%.

Keywords

Composite Material, Encapsulation, Solar

1 INTRODUCTION

Recently progressively more researchers focused their attention on solar energy applications for vehicles. Various solar vehicle prototypes have been built and tested, mainly for racing and demonstrative purposes [1, 2]. Due to this strong demand in sustainable energy sources, solar cells have been the object of increasing development during the last decade [3]. Considering their intrinsic physical properties such as light-weight, mechanical flexibility and semi-transparency, these devices may create innovative opportunities for energy applications. The Sasol Solar Challenge (SSC) created an opportunity for South African universities to design these solar powered vehicles in a concurrent engineering (multi-disciplinary team) [4] environment. South Africa is fortunate to have 6 to 10 hours of sunlight per day, which is one of the highest rates of sunshine in the world. This makes South Africa an ideal venue for such an event which further highlights the potential of using the sun as a source of energy in South Africa. The sun emits a tremendous amount of energy with approximately 1kW of power in the form of electromagnetic radiation available per square meter. This is in essence free, renewable and untapped energy. However, to utilise solar energy, we require a method to capture and transform this energy in a cost effective way. The first two solar cells were already produced in 1941. These cells could however only convert about 1% of the available energy into usable electricity. Today, it is possible to find commercially available solar cells with efficiencies of up to 24%, with space grade cells having bettered this with efficiencies of up to 42% [5]. There are a number of articles [6, 7, 8] explaining the encapsulation of solar cells, using a variety of manufacturing methods. Some of these have been patented for commercial applications. Figure 1 illustrates a typical solar cell encapsulation. This encapsulation method is to frame the solar cells in glass, sealed in EVA (Ethylene-vinyl acetate). Unfortunately, glass encapsulation is not feasible, due to the vehicle's weight restrictions (total dry weight ≤150 kg).

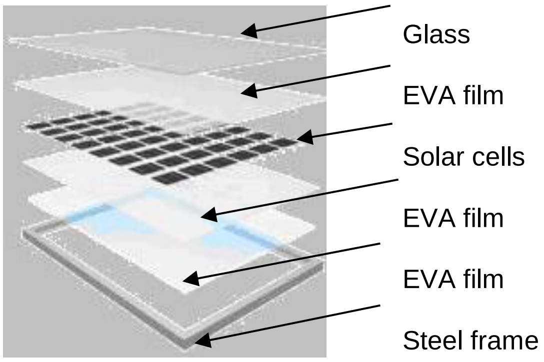

Figure 1 - Typical type of encapsulation used for solar cells that are fitted onto the roofs of homes

In 2010, the university's unmanned aerial vehicle (UAV) research group produced a solar powered UAV with a 14m wingspan. The wings incorporated 14% terrestrial solar cells encapsulated in composite material. A number of problems were identified, such as bubbles on the surface. This greatly reduced the efficiency of these solar cells. Building on their work, this research study was designed to address these challenges in order to maximize the efficiency of the solar cells, while protecting it mechanically. This solar vehicle's 514 monocrystalline cubic zirconia silicon (16.8% efficient) wafers cells, coated in clear glass (total thickness ±0.15 mm), produce approximately one kilowatt of power. The manufacturing challenge is to protect these cells from the terrestrial elements over a prolonged period of time. Solar cells are typically manufactured from a silicon wafer coated in glass, making them very fragile. Breakage is a common problem, with any cell cracking rendering the cells virtually useless and needing replacement. Figure 2 illustrates the solar cell layout and wiring. Composite materials are formed from two or more materials producing properties that could not be obtained from any one material [9].

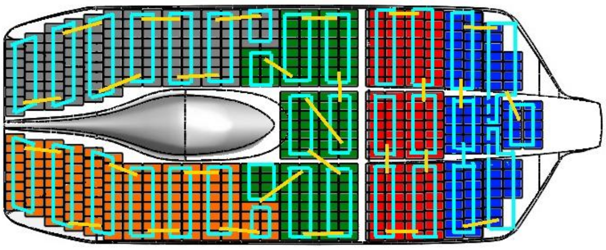

Figure 2 - Top-view of the solar cell layout and wiring design for the SSC vehicle

The increase in strength of the solar cell arrays in a lightweight manner, while mitigating losses on the solar vehicle were investigated. Glass fibre reinforced plastics (GFRP) are commonly used materials in view of their high specific mechanical properties and low cost. It was also used in this project. In this study various composite encapsulation methods were tested and evaluated.

2 EXPERIMENTAL SETUP AND DESIGN

The purpose of this experiment was to evaluate the performance of composite encapsulated solar cells, in terms of the energy efficiency and mechanical strength (hardness/toughness).

2.1 Experimental process

In order to test and evaluate this composite encapsulation method the following steps were taken as shown in figure 3:

1. Electronically, thermally and mechanically evaluate the solar cells before encapsulation as benchmark
2. Encapsulate the solar cells with composite materials
3. Evaluate the energy and thermal performance of the encapsulated solar cells
4. Mechanically evaluate the encapsulated solar cells with a ball drop impact test.

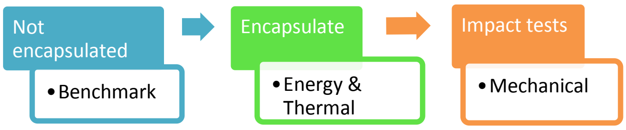

Figure 3 - Experimental process for investigating the effects of composite materials in solar cell encapsulation

The encapsulated cells were first electronically evaluated, while using an artificial light source. Thereafter, it was mechanically assessed using a ball drop impact tester. The conditions were controlled and monitored throughout the experiment.

2.2 Experimental materials

In these experimental material lay-ups the top layers were 49g glass, with variations in the middle and bottom layer. The first step in the lay-up process was to wet the selected laid out composite materials as shown in table 1. Then the 2mm Airex core was added and painted with Alutex (pre-impregnated with epoxy). Only then the solar cells could be perfectly placed onto the core.

Sample #	Laminate Lay-up
1	None (Benchmark)
2	290g Alutex / Airex / 49g glass
3	290g Alutex / Airex / 163g glass
4	290g Alutex / Airex / 25g glass
5	280g Glass / Airex / 49g glass
6	280g Glass / Airex / 163g glass

Table 1 - Laminate lay-up for the composite encapsulated test specimens

Thereafter, 49g fibreglass was laid out and the peel-ply added. A perforated release film and air-bleed were then added, before the entire lay-up was vacuum bagged. During the initial test lay-ups the epoxy began to gel during the lay-up. As the hardening of the epoxy is an exothermic reaction, a successful attempt in slowing down this reaction was made through placing the mixing cup into a small plastic bowl of water. Then by freezing the water the gel time extended from 35 minutes to approximately 50 minutes, thus giving more time for lay-up. A further observation was with regards to the peel-ply and its correct use. The peel-ply is placed over the cell and it is what gives the surface a consistent matt finish. Therefore, the peel ply should be placed over the cells properly to cover them entirely.

2.3 Solar cell encapsulation

Vacuum bagging was used to allow for uniform pressure across the solar cells during encapsulation. This was achieved by sealing a plastic film over the wet laminate lay-up; and onto the solar cells as shown in figure 4.

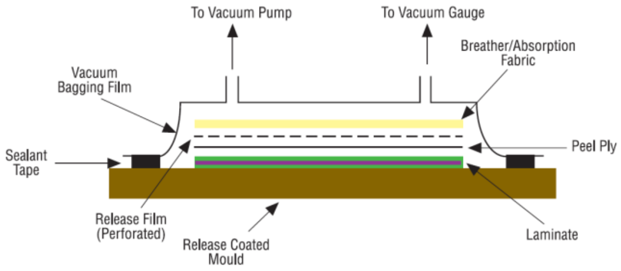

Figure 4 - Composite encapsulation of the solar cells using vacuum bagging method

The air under the bag was extracted with a vacuum pump allowing the laminate to consolidate under pressure. Figure 5 shows the vacuum pump that was used for the process. The benefit of this process was that higher fibre content laminates could be achieved compared to standard wet lay-up methods, reducing the amount of resin required and therefore reducing the weight of the lay-up. It also helped to reduce the void contents compared to normal wet lay-up.

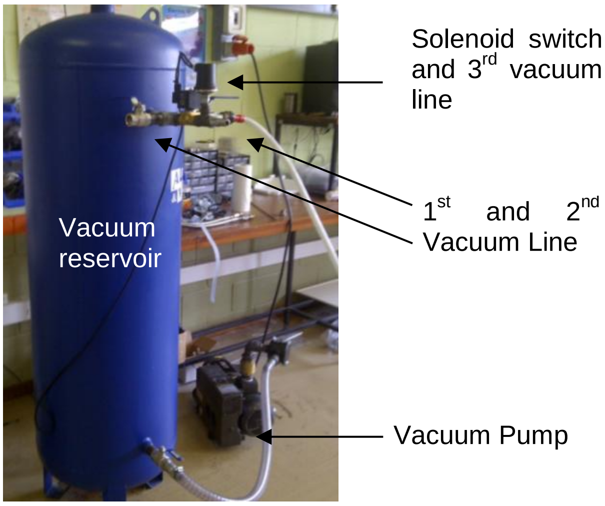

Figure 5 - The vacuum pump used in the encapsulation process

The vacuum lines were connected to the surface of the lay-up inserted into a vacuum bag and the solar cells were encapsulated as shown in figure 6.

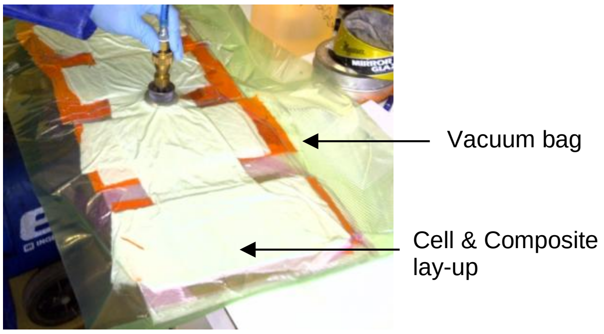

Figure 6 - Vacuum bagging to encapsulate the solar cells with composite materials

Through theory and as per advice from industry several composite materials were selected to evaluate.

2.4 Electronic and thermal test

The cells were tested in the light box using a standard multi-meter as shown in figure 7. The cells were placed in the centre of the box and connected to the clips which are coupled to the multi-meter.

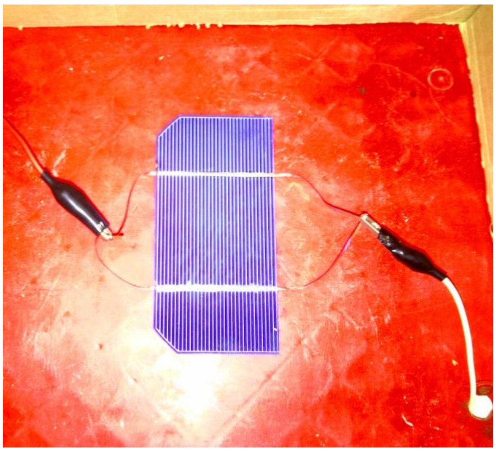

Figure 7 - Experimental setup for the electronic and thermal test with a un-encapsulated solar cell

The initial temperature was kept within the tolerance, and no problems were identified. The temperature was measured using an infrared (thermometer) gun.

2.5 Mechanical strength test

In order to evaluate the encapsulated solar cells' mechanical strength, the cells were placed directly in the centre on small pedestals below a vertical pipe as shown in figure 8. A steel ball was dropped through the pipe, onto the solar cell, based on the terminal velocity of a hailstone. Thereby, the solar cells then acts like a supported beam with the impact load applied at the centre of the cell.

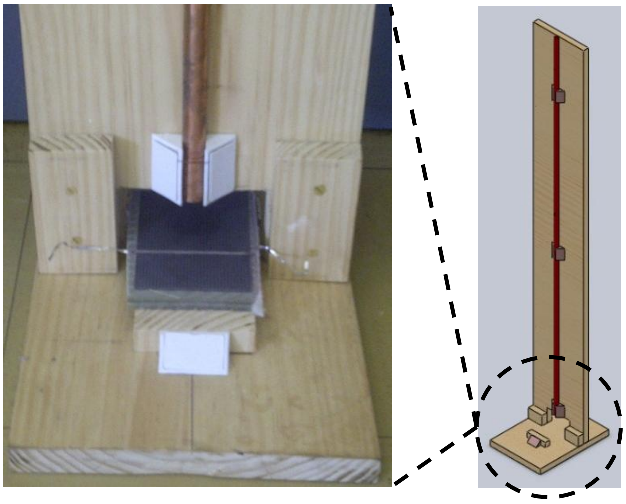

Figure 8 - Experimental setup for the Ball drop impact test

In order to simulate the impact of a hailstone, the height of the experimental ball drop impact tester first had to be calculated using the following equations. For an object moving through air at a high speed, there exists a resistive force which is proportional to the square of the speed as per eqn. (1)

$$R = \frac{1}{2} D \rho A v^2 \tag{1}$$

As per the definition of a free falling object at terminal velocity, the resistive force and gravitational acceleration are balanced as per eqn. (2) and the acceleration by eqn. (3)

$$\sum F = mg - \frac{1}{2} D \rho A v^2 \tag{2}$$

$$a = g - \left(\frac{D \rho A}{2m} \right) v^2 \tag{3}$$

At the terminal velocity (V_t) the acceleration a=0 and therefore the terminal velocity can be expressed as given by eqn. (4)

$$V_t = \sqrt{\frac{2mg}{D \rho A}} \tag{4}$$

During a hailstone the terminal velocity is around V_t=14 m/s. Thus the height required for a hailstone to reach terminal velocity could be determined as calculated per eqn. (5).

$$\begin{gathered} V_t^2 = U^2 + 2as \\ \{u = 0; a = g = 9.81 m/s\} \\ 14^2 = 0 + 2(9.81)s \\ \therefore s = 9.99m = y_{HS} \end{gathered} \tag{5}$$

Therefore, the height required to simulate the terminal velocity of a hailstone was found to be s=y_{HS}=9.99m. From this the potential energy of the hailstone could be calculated as per eqn. (6)

$$U_{g_{HS}} = m_{HS} g y_{HS} = 47.04 mJ \tag{6}$$

Knowing this, the required height for a steel ball (m_R=3.53g) to reach the equivalent terminal velocity could be calculated as per eqn. (7) and eqn. (8)

$$U_{g_R} = m_R g y_R = (34.63 y_R) mJ \tag{7}$$

$$\begin{gathered} U_{g_{HS}} = U_{g_R} \\ 47.04(10^{-3}) = 34.63(10^{-3}) y_R \\ \therefore y_R = 1.358 \approx 1.36m \end{gathered} \tag{8}$$

The height of the experimental ball drop impact tester was calculated to simulate the impact of terrestrial elements such as hailstones or debris shooting up from the road. Impact energy was not recorded during the test, since this research was concerned with whether laminates will mechanically withstand the impact of the ball drop test. The laminate(s) showing no signs of damage will be compared with respect to ease of processing and weight. The heavier the fabric weight the more epoxy required. Thus, the fabrics with the lowest possible fibre volume must be selected.

3 EXPERIMENTAL RESULTS AND DISCUSSION

The first step was to electronically, thermally and mechanically test the solar cells, before encapsulation to have benchmark for the following experiments. Table 2 shows the output results of the solar cells prior to encapsulation.

#	Open Voltage [mV]	Short Current [A]	Initial Surface Temp. [°C]	Final Surface Temp. [°C]
1	508	1.05	23	38
2	494	1.01	23	44
3	509	0.96	23	48
4	500	1.09	24	44
5	548	1.18	23	36
6	540	1.20	23	43

Table 2 - Results for un-encapsulated solar cells

In the second phase the solar cells were encapsulated as illustrated in figure 9. This solar cell was encapsulated using Alutex fabric as opposed to the green glass that has transparent cores.

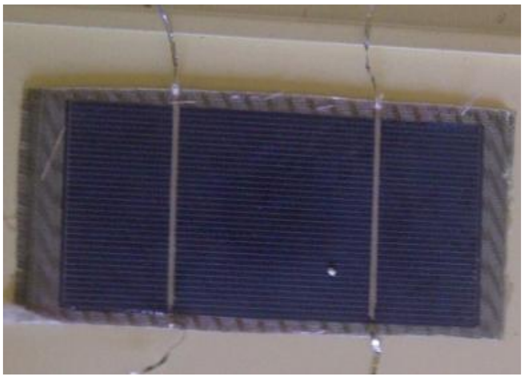

Figure 9 - Composite encapsulated solar cell

Table 3 shows the output results from the encapsulated set of samples. Sample 1 has been left un-encapsulated as benchmark for the experiment.

#	Open Voltage [mV]	Short Current [A]	Initial Surface Temp. [°C]	Final Surface Temp. [°C]
1	508	1.05	23	38
2	470	0.99	23	33
3	503	0.95	24	34
4	490	1.05	24	35
5	536	1.16	23	34
6	516	1.17	23	33

Table 3 - Results of encapsulated solar cells before impact testing

Considering the data in the table, it can be seen that the final surface temperature of the encapsulated solar cells decreased compared to the benchmark. The average temperature of the five cells prior to encapsulation averaged around 43°C, whereas after encapsulation had an average surface temperature of 33.8°C. This is almost a 10°C difference. Table 4 compares the encapsulated and un-encapsulated electronic outputs. It is well documented that an increase in the surface temperature of the solar cells can adversely affect the electrical efficiency [10]. Therefore, the surface temperature should be kept to a minimum.

#	Voltage loss [mV]	Voltage loss (%)	Current loss [A]	Current loss (%)
1	0	0	0	0
2	24	4.86	0.02	1.98
3	6	1.179	0.01	1.042
4	10	2.00	0.04	3.67
5	12	2.189	0.02	1.69
6	24	4.44	0.03	2.5
Avg.	**15.2**	**2.93**	**0.17**	**2.18**

Table 4 - Comparison of encapsulated composite lay-ups on solar cells with variations in the middle and bottom layers

After composite encapsulation an average voltage loss of 2.93% and an average current loss of 2.18% were recorded for the encapsulated cells. These samples were then tested after a ball drop impact test. Figure 10 graphically illustrates the voltage- and current loss in percentage relative to the encapsulated solar cells. Sample 2 had the largest voltage loss of 4.86% followed by sample 6. Sample 4 had a current loss of 3.67%. Table 5 shows the output results after each sample has undergone impact testing.

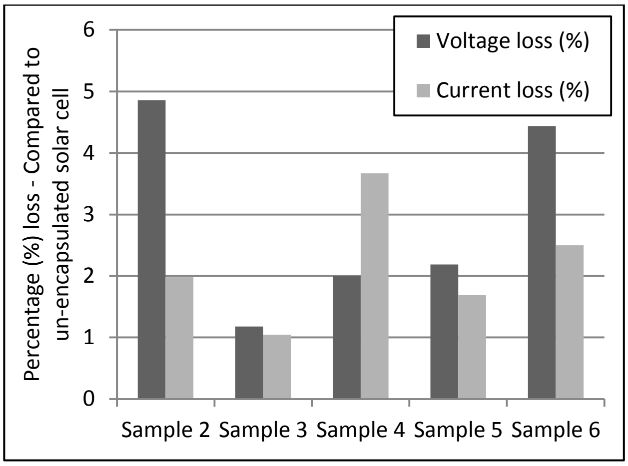

Figure 10 - Voltage and current loss (%) of encapsulated solar cells compared to un-encapsulated solar cells

#	Open Voltage [mV]	Short Current [A]	Initial Surface Temp. [°C]	Final Surface Temp. [°C]
1	-	-	-	-
2	517	1.00	23	33
3	512	0.98	25	36
4	201	0.47	25	37
5	556	1.16	24	36
6	559	1.22	26	36

Table 5 - Results of solar cells after impact testing

The un-encapsulated (benchmark) solar cell's performance could not be tested post-impact, since the solar cell was completely destroyed. From the encapsulated solar cells only sample 4 showed any affect from the impact. There was however no visible damage to the cell, thus indicating that a micro-fine hairline crack(s) has formed within the laminate. Therefore, the impact test was effective in determining whether or not the encapsulation will protect the solar cells.

4 CONCLUSION

The effects of composites reinforcement, electrical efficiency and thermal efficiency of the solar cells were evaluated. Impact testing to simulate a hailstone showed that a fibreglass sandwich panel structure will protect the surface of the cells, while reducing their efficiency by less than 5%. Future research should include other innovative processing techniques such as the reflow for cell soldering, resin infused moulding for cell encapsulation and also silicon encapsulates.

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6 BIOGRAPHY

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