HRCEV: HIGH-RATE COMPOSITES FOR ELECTRIC VEHICLES

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ABSTRACT

In the HRCEV (High-Rate Composites for Electric Vehicles) project, funded by Innovate UK, a novel manufacturing process was implemented at pilot-scale to develop a lightweight composite battery module enclosure. Using rapid-cure epoxy prepregs, WAE's patented 223™ manufacturing technology enabled high-rate forming and curing of two-dimensional laminates into three-dimensional components with perpendicular faces and deep draw depths not easily achievable with other manufacturing methods. In this feasibility study, technical requirements for both manufacturing and product development were identified, and materials were developed to meet those demands. Novel tooling design allowed for control of the cure state in the flat laminate, enabling hinged areas to fold and undergo a secondary cure within a dynamic bending jig. Several parameters, including stacking sequence and degree of cure, were identified as influential to the quality of the corners of the module case. The final product achieved structural performance requirements during FEA simulation and remained within geometric tolerances following manufacturing. When compared against other established manufacturing processes for battery module enclosures such as autoclave and compression moulding processes, life cycle and cost analyses demonstrated reduced environmental impact of the 223™ process and greater commercial viability in serial production with a high potential for automation.

1 INTRODUCTION

Amongst rising fuel costs and a legislative drive towards NetZero, the use of composite materials to reduce component weight is critical to the growth of the electric vehicle (EV) industry and achievement of emissions targets. However, composite components are often restricted in implementation due to high raw material cost, low rates of production, as well extensive skilled labour requirements in traditional manufacturing methods [1]. As a result, composite component costs remain elevated, inhibiting deployment of parts within the automotive industry.

Currently, cost-effective materials comprising automotive battery box enclosures are predominantly steel and aluminium [2]. Though these materials enable short takt-times, they can be subject to geometric design limits and require significant tooling investments. Additional fittings, fasteners, and other materials may be required in metallic configurations, so the overall metallic component weight is often greater than an equivalent integrated composite solution [3]. Thus, lightweighting of components to increase efficiency and range of EVs serves as a further driver of composite manufacturing technology development.

By developing and implementing a composites manufacturing process with a short takt-time and high production volume, composite battery module enclosures may become commercially competitive with metallic configurations but with lower weights. The project High-Rate Composites for Electric Vehicles (HRCEV) addressed the need for increasing the rate of composite battery module enclosure manufacturing through implementation and development of patented 223™ forming technology.

Additionally, the environmental impacts of manufacturing were examined and evaluated through life cycle analysis (LCA) of both metallic and composite configurations.

Funded by the 2022 Innovate UK Eureka-Eurostars program and the Korean Institute for the Advancement of Technology (KIAT), the project was led by WAE Technologies Ltd., (WAE) and supported by the Lightweight Manufacturing Centre (LMC) in manufacturing and testing and Hankuk Carbon Co. Ltd. in South Korea and Hankuk Composite UK Ltd. as the material developer and supplier.

2 OBJECTIVES

Within 18 months, the aim of this project was to complete a product definition and feasibility study for a lightweight, composite battery module enclosure with sufficient performance at high production volume. As outlined in this paper, the project achieved four objectives:

1) Development of materials suitable for rapid compression moulding of hinged hybrid preforms.
2) Design and manufacture of a composite battery module casing demonstrator with 223™ process technology.
3) Comparison of environmental impact to a baseline model through life cycle analysis.
4) Comparison of metallic and composite manufacturing processes through cost modelling analysis.

3 223 ™ PROCESS TECHNOLOGY

In a novel approach to manufacturing and assembly, 223™ technology enables rapid forming and curing of three-dimensional components [4]. Rather than placement of plies within a complex mould, near-net-shape two-dimensional blanks are compression-moulded as flat panels, followed by forming and curing with a dynamic tooling jig to final form, as shown in Figure 1.

In this project, selective curing of “hinge zones” and sidewalls on the flat laminate enabled forming into the battery module case geometry, followed by secondary curing of the hinge zones. As estimated by WAE, 223™ technology is up to 50 times faster than traditional aerospace-grade methods, which lay down material at roughly 10 to 20 kg per hour [3].

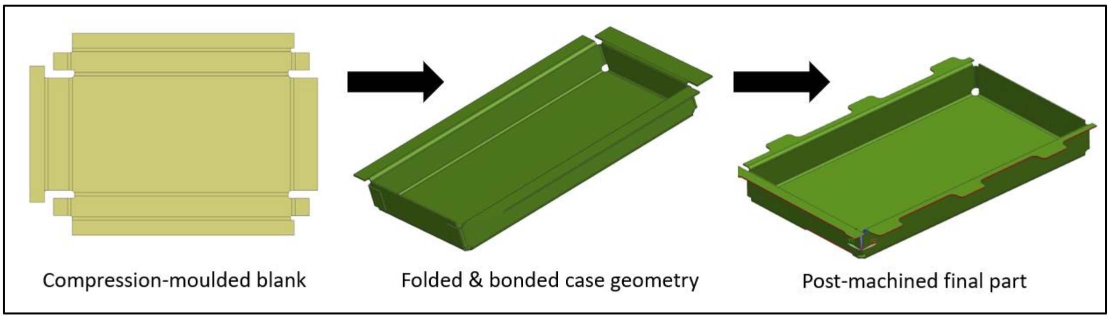

Figure 1. Example of 223™ process technology

4 MATERIALS & METHODS

4.1 Materials Development

As a design and feasibility study, the first phase of the project mandated specification of technical requirements suitable for the battery module enclosure. This entailed requirements for both the manufacturing process, such as cure cycle time, viscosity, and outlife, as well as the product, including structural properties, fire retardance, and electrical resistance.

Resin and reinforcement material and format were customized and formulated according to product requirements. Prepreg materials were manufactured by Hankuk Carbon Co., Ltd., and provided to the

LMC for further testing. Two prepreg materials were down-selected and implemented in this project: a carbon fibre/epoxy prepreg (CFRP) for high structural performance and EMC compliance and a glass fibre/epoxy prepreg (GFRP) for electrical insulation. The reinforcements for the CFRP and GFRP consisted of a 2/2 twill weave fabric of 200gsm CF3327 fibre and a plain weave 400gsm glass fibre fabric, respectively. Both prepregs contained the rapid-curing and non-halogen fire-retardant Hankuk FC9X-R epoxy resin system with a cure cycle of 4 minutes at 150 °C [5].

Experimental testing of materials on a coupon level was carried out by the LMC to examine bending behaviour in selected geometries with a dynamic folding jig. Bending behaviour was correlated to material properties such as cure state through material characterization methods including differential scanning calorimetry (DSC) and fibre volume fraction analysis. Hinge corner quality and the effects of wrinkling were defined and analysed through conformance to geometric tolerances and mechanical strength testing and compared with coupons manufactured with a similar geometry in a traditional hand-layup/autoclave process.

4.2 Product Design

To form "flat-pack" laminates, novel press tooling was designed and manufactured for compression moulding that enabled differentiated cure states between hinge zones and sidewalls in an industrial press at the LMC (*PEI 340t press, Pinnette PEI, France*), as shown in Figure 2a and 2c. Temperature gradients of the tooling were simulated with computational fluid dynamics (CFD) tool and validated through experimental testing. Press tooling for moulding of near-net-shape flat laminates was machined from AL 6082-T6 with channels containing 3D-printed polymeric inserts (Ultem 1010) (Figure *2*b) that prevented hinged areas from reaching full cure state. To optimize the cure cycle, degree of cure and hardness measurements indicated polymerization level in hinge zones following compression moulding.

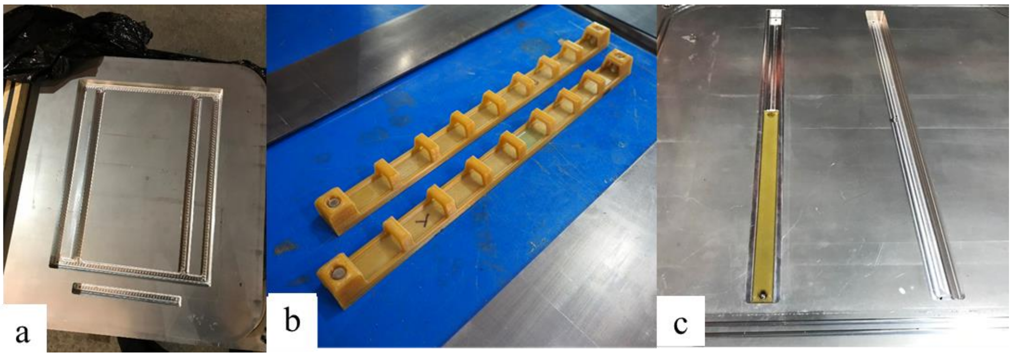

Figure 2. (a) Tooling for demonstrator (b) polymer inserts and (c) assembled coupon tooling.

Parallel to press tooling development, a composite battery module enclosure was designed to replace an aluminium product of similar geometrical, functional, and structural product requirements (Figure 3a). Detailed design consisted of stacking sequence definition and modelling of loadings through finite element analysis (FEA), as well as an experimental study of adhesive bonding solutions.

The final stage of demonstrator manufacture entailed an iterative design of a full-scale bending jig based on results of previous trials and product requirements to secure process technology. The jig was designed and manufactured by MetLase (*Sheffield, UK*) to allow folding and curing of battery module enclosures in one step (Figure 3b and c). The folding jig ensured that the hinges were fully supported and pre-compressed during folding, thus achieving the conditions required for full consolidation and the required angular tolerances. Moreover, the use of a demoulding feature allowed for easy part extraction without the need to use pronounced draft angles as adopted in compression moulding. Following full-scale demonstrator manufacture, "cradle-to-gate" life-cycle analysis and cost-modelling examined environmental impact and commercial viability of the process.

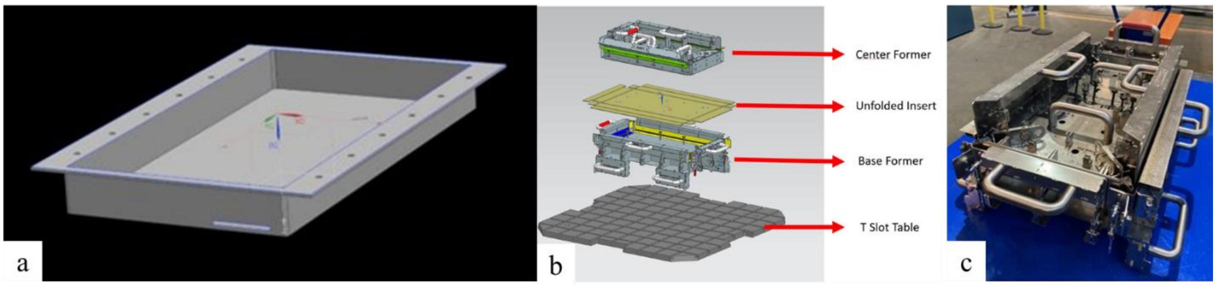

Figure 3. (a) Composite battery module case design (b) MetLase bending jig - exploded view (c) manufactured jig

5 RESULTS AND DISCUSSION

Preliminary material and process trials at coupon scale indicated that at a constant cure state, fibre orientation angle, ply thickness, and ratio of bend radius to thickness were found to have the greatest effect on hinged corner quality and strength when utilizing the bending jig. As hinged corners initially exhibited significant deformation during forming, material and laminate properties such as cure rate and stacking sequence could be manipulated to enable perpendicular surfaces and minimize wrinkling around corners.

Mechanical testing of coupons manufactured with 223™ showed a reduction in strength of 50% compared to hand-layup manufacturing at the same thickness. This was likely due to the waviness in the hinges that was more predominant in the 223™ process than hand lay-up. Despite reduced strength, 223™ coupons still achieved required mechanical performance for the battery module enclosure. The coupon testing was also used to calibrate a Finite Element model to capture the different mechanical properties between the pre-consolidated sections and the hinges.

CAE analysis was then conducted to compare a baseline cast aluminium model with a 223™ formed composite module with selected materials and stacking sequence. Both static and modal results of the 223™ formed enclosure showed performances comparable to the baseline. For instance, 223™ showed a negligible reduction of 0.7% of the 1st eigenvalue and 1% of the second eigenvalue compared to the baseline aluminium model. The abuse static analysis showed very localised first ply failure for 223™ at the hinges, which was considered acceptable given the stage of development.

In this project, a full-scale demonstrator of an EV battery module enclosure manufactured with 223™ technology enabled an overall weight savings of 10% compared to a similar aluminium product (Figure 4). The product not only achieved desired weight savings but was within tolerance limits for planarity, dimensions, and face angularity.

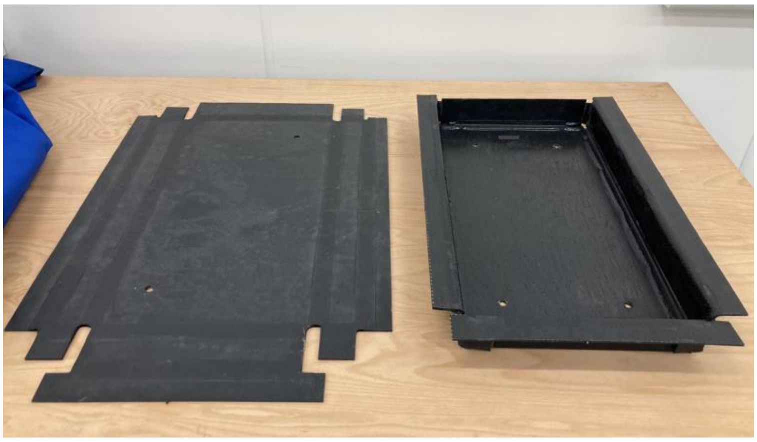

Figure 4. Full-scale 2D and 3D composite battery enclosures.

5.1 Life Cycle Analysis

The goal and scope of the LCA (ISO 14044:2006) were to assess the environmental impact of the 223™ manufacturing process and compare to other methods used to produce similar designs, namely cast aluminium, compression moulding, and autoclave curing. A "cradle-to-gate" approach was used, covering only the raw materials manufacture, transportation, and final product manufacture.

The functional unit considered was the WAE-designed battery module enclosure, described in Section 4.2, made of either (i) CFRP or (ii) GFRP. The considered input and output flows and process descriptions are shown below in Figure 5 and 6. Only energy and material input/output flows used in the process were considered in the analysis. No ancillary materials (e.g., consumables, release agents, mould cleaning, peel ply, demoulding, etc.) were considered as impact was assumed to be minimal.

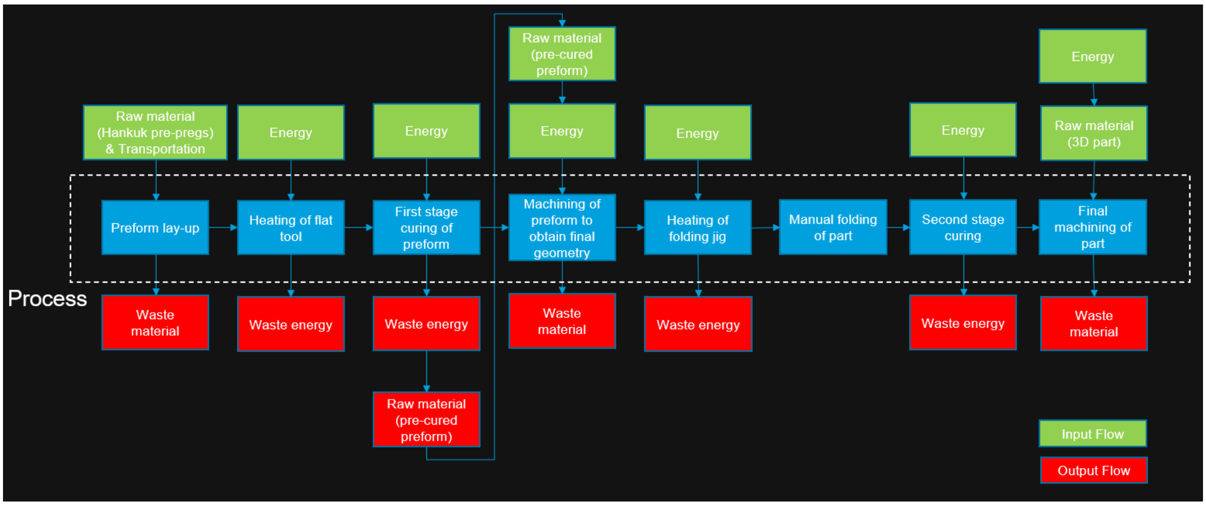

Figure 5. Process flow of 223^{TM} manufacturing process.

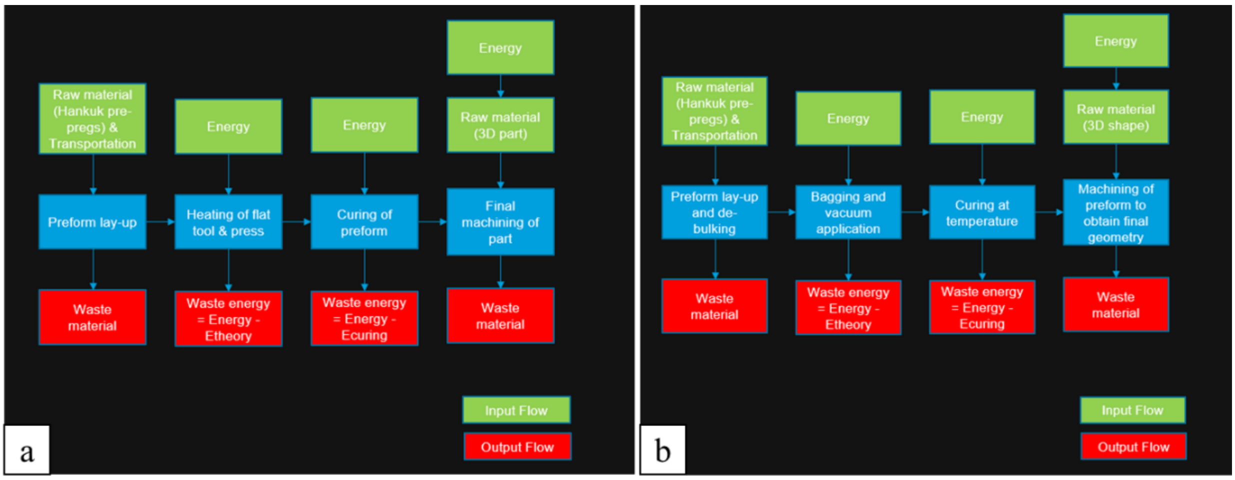

Figure 6. Process flow of (a) compression moulding and (b) hand layup with autoclave curing.

The impact category used in this study was kg of CO_2-equivalent emitted during either (a) manufacturing of a 1-off functional unit including the energy required for production line set-up (i.e., energy to bring equipment from ambient to working temperature) or (b) manufacturing of the nth functional unit in serial production with equipment already at working temperature (Impact Assessment Method: GWP 100a).

The LCA used raw material manufacturing data provided by Hankuk Carbon Ltd. for both CFRP and GRFP base materials. The kg of CO_2-equivalent generated to produce CF and GF-reinforced fire resistant pre-pregs are respectively 17.5 and 3.75 Kg CO_2 eq/Kg. The same materials were used for all composite manufacturing processes considered in this study. The energy consumption (EC) of each process in this study is shown below in Figure 7.

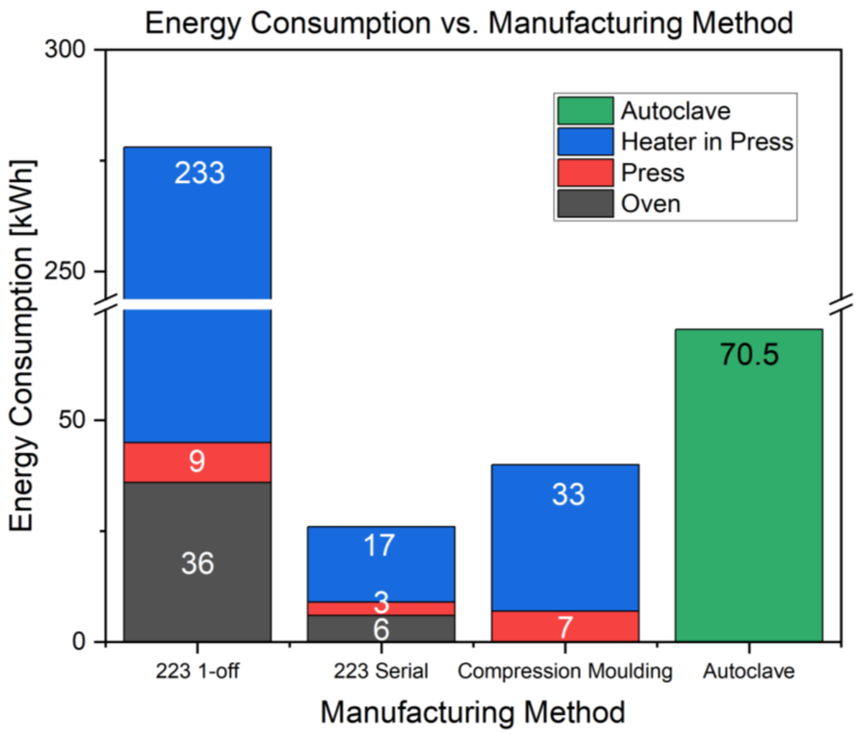

Figure 7. Total Energy Consumption of Manufacturing Methods

The resulting kg of CO_2 eq/kg for the energy used to produce one functional unit per kilogram of raw material ($CO_{2eq}Process$) was calculated with Equation 1, where $Weight_{unit}[kg]$ is the total amount of raw material used in the process (including scrap). The impact values determined by the electrical energy ($CO_{2eq}EP$) used for the manufacturing of a composite functional units 223™, autoclave curing, and compression moulding were extracted from an online calculator [6].

$$CO_{2eq}Process\ [kg\ of\ CO_{2eq}/kg] = EC\ [kWh/unit] * CO_{2eq}EP\ [kg\ of\ CO_{2eq}/kWh] / /Weight_{unit}[kg] \quad (1)$$

The impact values for transportation ($CO_{2eq}RawMat_{Transp}$) were estimated with Equation 2, assuming that all materials had been transported from locations of production (South Korea) to the UK where final production of the functional units occurs. $CO_{2_{eq}}Freight$ is equivalent to 0.045 $kg\ of\ CO_2eq/unit * 1000km$, whilst the freight distance travelled was estimated to be 22650 km for the composite materials [7-8].

$$CO_{2eq}RawMat_{Transp}\ [kg\ of\ CO_{2eq}/kg] = CO_{2eq}Freight\ [kg\ of\ CO_{2eq}/(unit*1000km)]/Weight_{unit}[kg]*Distance\ Travelled\ [km]/1000 \quad (2)$$

Combining equations 1 and 2, the total of CO_{2eq} /kg for the 223™– 1-off process ($CO_{2eq}223_{1off}Total$) for both CFRP and GFRP was determined with Equation 3.

$$CO_{2eq}223_{1off}\ Total[kg\ of\ CO_{2eq}/kg] = CO_{2eq}Process\ [kg\ of\ CO_{2eq}/kg] + CO_{2eq}RawMat_{Transp}\ [kg\ of\ CO_{2eq}/kg] \quad (3)$$

The results for CFRP and GFRP are 39.5kg and 25.7 kg, respectively, as shown in Figure 8.

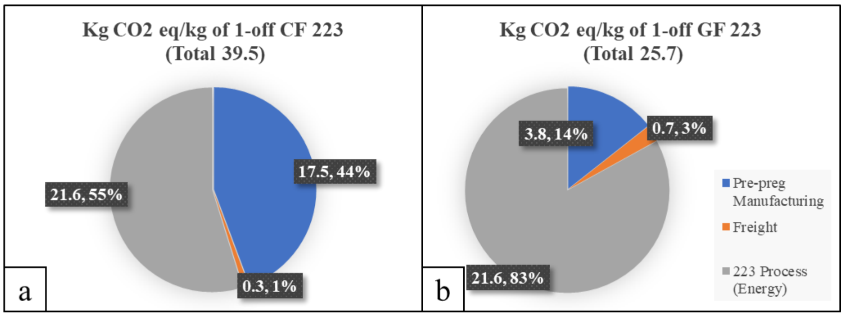

Figure 8. Kg CO_{2eq}/kg for 1-off 223™ production with (a) CFRP and (b) GFRP.

Using similar approach as for the 223™ 1-off and the energy consumption reported in Figure 7, the environmental impact for 223™ –serial production is 19.8 kg and 6.1 of CO_2 eq/kg for CFRP and GFRP, respectively (Figure 9).

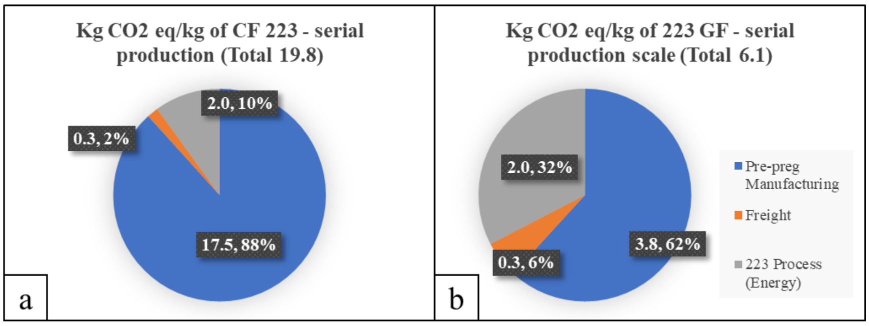

Figure 9. Kg CO_{2eq}/kg for serial 223™ production with (a) CFRP and (b) GFRP

The environmental impact for hand-layup and autoclave curing is 23.2 and 9.9 kg of CO_{2eq}/kg for CFRP and GFRP, respectively, as shown in Figure 10:

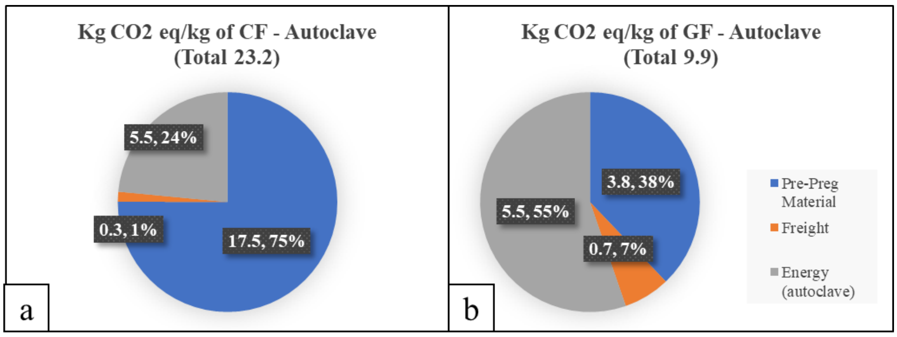

Figure 10. Kg CO_{2eq}/kg for autoclave manufacturing with (a) CFRP and (b) GFRP

The environmental impact for compression moulding is 21.0 and 7.2 kg of CO_{2eq}/kg for CFRP and GFRP, respectively, shown in Figure 11.

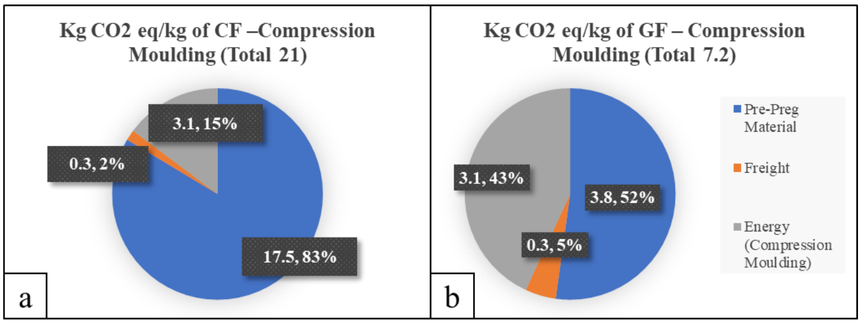

Figure 11. Kg CO_{2eq}/kg for compression moulding with (a) CFRP and (b) GFRP

The results of the four processes for both GFRP and CFRP, as well as cast aluminium, are reported in Figure 11. Kg of $CO_{2\ eq}$/kg for cast aluminium was assumed to be 14.77 [9].

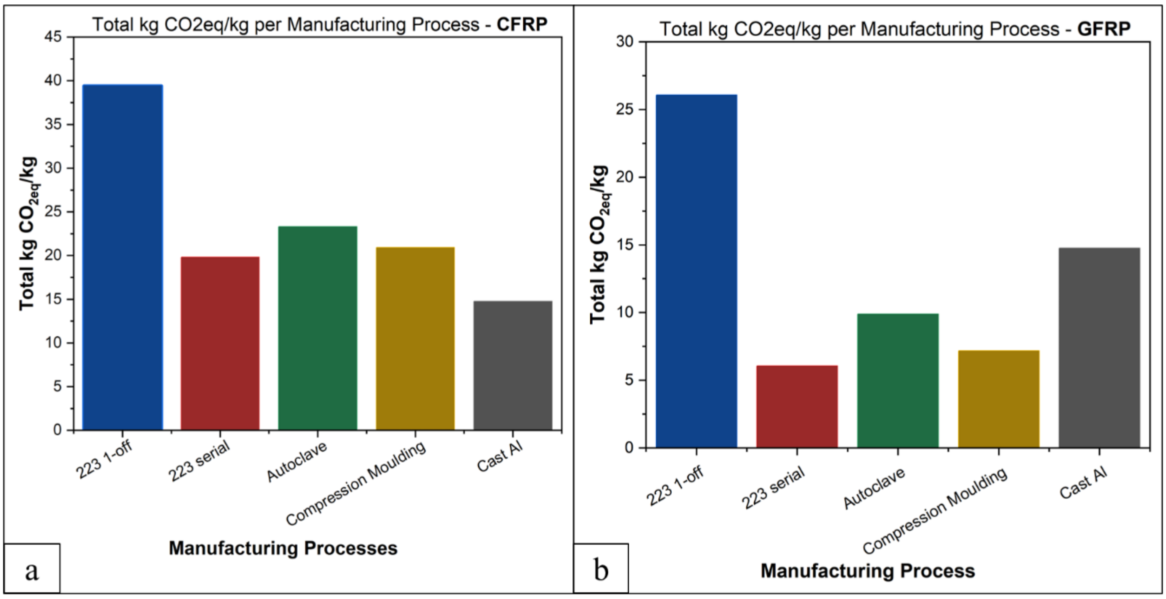

Figure 12. Total kg CO_{2eq}/kg for all manufacturing processes with (a) CFRP and (b) GFRP.

The manufacturing of a 1-off CF 223™ functional unit generates more than twice the levels of CO_2 emissions than casting of aluminium or the other examined analysed manufacturing processes. This is due to energy required to bring the process from ambient to operation conditions. The use of GF instead of CF reduces the total value of CO_2 produced.

The LCA obtained for 223™ serial production shows a smaller environmental impact than autoclave curing and compression moulding. Moreover, the 223™ process required the least amount of ancillary materials compared to the other manufacturing processes. For GFRP materials, the LCA follows a trend similar to CFRP with total values drastically less that the composite manufacturing processes as well as aluminium casting.

5.2 Cost Modelling

A cost model was developed by WAE to predict the Bill of Materials (BOM) costs of a functional unit produced with the 223™ process, autoclave curing, and compression moulding. The cost model for the manufacturing of a composite part considered various aspects of the production process, including the cost of raw materials, labor, energy consumption, and equipment. The model examined specific requirements of each process, such as unique curing cycles, specialized tooling, and the need for precise temperature and pressure control. To accurately estimate the cost of production, the model also factored in the yield rate and scrap rate of each process. In addition, the model included the cost of post-processing steps. Finally, the model incorporated a profit margin to provide a realistic estimate of the total cost of production for the composite part. Overall, this cost model provides a comprehensive and detailed analysis of the various factors that contribute to the cost of manufacturing a composite part.

The material cost (C_{mat}) was estimated by quantifying the required weight of material ($Weight_{TotComposite}$) needed to make one functional unit, including any material waste, by extracting the geometry of the part either from a CAD file or a drawing specifying primary dimensions. Also considered were the cost of the raw material per kg ($C_{composite}$) and ancillary materials ($C_{ancillary}$), such as:

1. For autoclave process - release agent, breathers, sealant tape, vacuum bags.
2. For compression moulding - bonding and release agent.
3. For 223™ - release agent.

An estimation of the material consumption was derived through Equation 4.

$$C_{mat}[£]=C_{ancillary}[£]+C_{composite}[£/kg]*\ Weight_{TotComposite} \tag{4}$$

The tooling investment costs ($C_{tool_{inv}}$) were based on quotes either received from suppliers or estimates based on historical data available at WAE for similar tools and moulds. In particular:

1. For the autoclave process, a tooling cost of £3,400 was assumed based on material quantities needed to create a male mould, machining required, and labour costs estimations.
2. For compression moulding, a tooling cost of £10,000 was assumed based on the use of a two-part mould made of materials capable of withstanding a high pressure and high temperature environment with minimal thermal expansion mismatch to the composites being formed.
3. For the 223™ process, a total cost of £9,000 was assumed, based on quotation for the flat tool (£3,000) including 3D-printed polymer inserts, and for the folding jig (£6,000).

The impact of the tooling investment cost on the production quantities was depreciated by the number of parts during production that can be manufactured using a single tool, providing a contribution cost of tooling per piece ($C_{tooling}$), shown in Equation 5.

$$C_{tooling}=\frac{C_{tool_{inv}}\frac{N}{N_{life}}}{N} \tag{5}$$

N (nominally 100, 1000, 10000 in this study) and N_{life} were the total number of parts manufactured in a manufacturing cycle and number of parts manufactured during the lifetime of the tooling, respectively. The investment costs required to secure the equipment were:

1) For the autoclave process, a 1m x 1.2m 200 °C 10 bar autoclave valued at £80,000.
2) For compression moulding, a 1.2m x 0.8m, 250T, 180 °C Oil heated press valued at £90,000.
3) For the 223™ process, a 1.2m x 0.8m, 250T, 180 °C Oil heated press, valued at £90,000 and oven (2m x 2m x 2m, 150 C), worth £15,000.

$C_{Operating}$ is the sum of all operating costs of the machines, defined as in Equation 6.

$$C_{Operating}[£]=\sum_{i=0}^{m}C_i=\sum_{i=0}^{m}\left[A_{hi}[hr]*(C_h\left[\frac{£}{hr}\right]+P_{cons}[kW]*C_{kwh}\left[\frac{£}{kW}\right])\right] \tag{6}$$

- A_{hi} is hours of operation of the machine during the process.
- C_h is the hourly cost of the machine considering the initial value of the machine and a linear depreciation deriving an annual equivalent cost of the machine.
- P_{cons} is the power consumption of the machine in kW.
- C_{kwh} is the energy cost per kWh to operate the machine.

Finally, the labour costs estimation C_{labtot} was based on the activity-based costing methodology [10]. The total worker hours ($T_{manhours_n}$) required to complete each process step for 223™ was measured by LMC during the HRCEV project, and compression moulding process times were based on historical data available at WAE. Data utilized for autoclave manufacturing was selected from a previous study at NASA [11]. Total worker hours are shown in Table 1.

Process Time ($T_{manhours_n}$)	**Prepreg & Autoclave [hr]**	**Compression Moulding [hr]**	**223™ [hr]**
	5.6	2.9	2.7

Table 1. Total time of human involvement per process.

The labour rate (L_{rate}) used in this study for all processes was assumed to be 15£/hr for a technician and 20£/hr per a supervisor. Percentage of utilisation of both roles were assumed to be respectively 85% and 10%. The cost of overhead (C_{oh}) was the cost accounted for the supervision percentage as well as the labour utilisation percentage.

$$C_{labtot}[£]=(\sum_{i=1}^{n} T_{manhours_n}[hr])*L_{rate}[£/hr]+C_{oh}[£] \quad (7)$$

The previous costs were considered to compute the Yield Cost (C_{yield}) as shown in Equation 8, with $Yield_{\%}$ $[-]$ assumed to be a fixed percentage accounting for a markup.

$$C_{yield}[£]=\left(C_{Operating}[£]+C_{labtot}[£]+C_{mat}[£]\right)*Yield_{\%}[-] \quad (8)$$

Once the cost model was applied to the three manufacturing processes considered, the total piece costs for each process was:

$$C_{tot}[£]=C_{yield}[£]+C_{tooling}[£] \quad (9)$$

This was computed for three different production volumes shown in Table 2 below:

		Prepreg & Autoclave [£]	**Compression Moulding [£]**	**223™ [£]**
Number of Parts	**100**	406.26	292.68	364.41
	1000	324.22	144.85	193.65
	10000	316.02	130.07	176.58

Table 2. Cost per part of each manufacturing process.

Three different production volumes were evaluated to check the economy of scale of the manufacturing processes, resulting in different amortisation rates for the equipment and tooling costs.

In summary, the 223™ process requires slightly higher investment costs compared to the other two processes but less consumables. This yields greater cost efficiency for 223™ than autoclave curing when manufacturing more than 100 components. Compression moulding is less expensive than 223™ at all production volumes.

6 CONCLUSIONS

As a result of this feasibility study, 223™ technology was developed and implemented to manufacture a battery module enclosure at high rate with a total weight reduction of 10% compared to an aluminium baseline model. Fire-retardant glass and carbon fibre epoxy prepregs were developed with cycle times of four minutes to achieve specified technical requirements for structural performance, function, and manufacturing, increasing the TRL of the 223™ process from 2 to 5. Moreover, the geometry of component produced with 223™ in this project demonstrated draw depths and surface perpendicularities not attainable in compression moulding.

An examination of the environmental impact of the 223™ process displayed greater sustainability through a lower output of carbon emissions in serial production than other manufacturing processes, which could reduce the overall embodied energy in electric vehicles. Cost analysis results showed that 223™ can be a viable alternative to autoclave curing even at low production volumes and is a competitive alternative to compression moulding at larger volumes. 223™ process costs may be further reduced through the introduction of automation and reduction of labour requirements.

The potential of this technology is significant as an enabler for cost-reduction of composite components, particularly for the automotive industry. Though this study focused on a battery module enclosure, other applications may include an automotive body-in-white or monocoques and extend to other industries such as defence. The intermediary "flat-pack" and semi-cured state of two-dimensional laminates during manufacturing allows for efficient packaging and storage of preforms for extended periods of time, as well as lower cost transport to the field or other end-use destinations. This technology can be easily automated, envisioned as a manufacturing line with a press for flat laminate compression moulding followed by secondary curing. The shorter cycle time achieved with this process, as well as a reduction in part count and assembly requirements, may allow greater competitiveness of composite parts within the automotive industry.

Future work will investigate modelling and characterization of bending behaviour across a range of materials and stacking sequences and seek to expand potential 223™ geometries and applications. Full-scale testing of the composite battery module enclosure manufactured in this project will further inform development strategies and potential applications. With the support of commercial partners, the technology will also be further expanded towards full automation and scaling to serial production.

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