INTRODUCING A NOVEL MANUFACTURING PROCESS FOR AUTOMOTIVE COMPOSITE COMPONENTS

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ABSTRACT

The aim of the present study was to show the development of a novel end-to-end production process for the manufacture of high volume, low-cost and lightweight structural component for the automotive industry. A process to produce discontinuous random fibres/epoxy resin composites parts with low takt time has been investigated. Resin and process optimisation through design of experiments, topology optimisation of the demonstrator design and a LCA assessment have been performed to achieve the project targets and characterise the new material. The cost, weight and takt time requirements were met although additional work to improve the mixing system is currently under investigation.

1 Introduction

The reduction of structural weight for future vehicles is essential to meet the demanding emission reduction targets and to enable electro mobility [1]. Lightweight, reduced tooling cost, resistance to corrosion and higher specific energy absorption in comparison to metals make fibre reinforced polymer composites a viable solution for the automotive industry [2]. Key obstacles in using polymer matrix composites in automotive body parts are cost, takt time and their potential loss of mechanical integrity when exposed to elevated temperatures of the e-coat process [3]. Different approaches have been suggested to eliminate this issue such as assembling the composite parts to the BIW after the e-coat process or lowering the temperature of the e-coat process [4]. However, none of these alternatives have been found viable for a high-volume production process.

"High-volume Lightweight Technologies for vehicle structures" (HiLiTe) was a three-year industrial research project, part-funded by Innovate UK, which began in March 2014. The project, led by Far-UK Ltd, aimed to address the aforementioned obstacles of the use of composites in the automotive industries. The project targeted to achieve at least 30% weight reduction on an existing steel component along with a 40% reduction in costs from traditional composite materials and processing. The challenging targets required to develop a novel end-to-end process for manufacturing high-volume and low-cost lightweight structural components for the automotive industry. This has to be an affordable process to manufacture structural automotive components under a takt time of 2 minutes. To enable integration with existing paint-shop process the material had to have high temperature capability. The approach was to produce a composite version of an automotive part focusing on three aspects: effective material development, design optimisation and efficient process development. The project aimed to developed a compression moulding polymer composite material based on an epoxy resin system and long discontinuous carbon fibres, offering the capability to run a net-shape manufacturing process. A Computer Aided Engineering model was built against the results of real-world component tests to validate the results. The consortium also included Expert AMT, the National Composites Centre, Tata Motors European Technical Centre and Warwick Manufacturing Group.

2. Method and Materials

The first phase of the project was focused on selecting the right component to be used as a case study for the project. It had to be a part that did not require a high-quality surface finish, and which could be produced with low takt time. A set of additional requirements were identified, such as potential weight saving, durability, and crash safety. Candidate parts were then rated against these specifications. The candidates were down-selected and the part with the highest ranking was chosen to be the demonstrator. In this case the bonnet inner had the best score among the other parts thus it was selected for the project.

To address the requirement for a low-cost production process, it was decided to use an automotive grade carbon fibre, the Panex-35 50K, as the reinforcement for the composite material. The resin system considered for the study was a commercially available 4-part epoxy resin system tuned to satisfy the requirements of the project. The aim was to obtain good fibre wet out, fast resin maturing, quick cure cycle and a satisfactory material flow during moulding. To achieve these requirements the resin system was optimised using a design of experiment (DoE) approach. Processing parameters such as fibre volume fraction, mixing time and press closing speed were considered fixed and other variables such as maturing agent, mix ratio, maturing temperature and cure temperature were varied to obtain the optimum solution for the processing.

Flat plaques were pressed using a shear edge tool to assess the material development in the first phase of the project. Coupons were machined and tested on tensile performance to characterise the mechanical properties along the transversal and longitudinal direction of the plaques. Once the material optimisation was completed, the process was assessed on a half-demonstrator tool before the full-scale trials.

Figure 1: A) Square flat plaque moulded with HiLiTe material produced during the material optimisation stage. B) half-bonnet inner produced to assess the upscale moulding parameters C) full-scale demonstrator.

To simulate a E-coat process, a group of tensile samples was conditioned in a Weiss chamber. The temperature was increased from room to 180°C with a 4°C/minute rate. Then the samples followed a dwell of 20 minutes at 180°C degrees before a 20-minute cooling down ramp to room temperature.

In the first part of the project, as a proof of concept, the fibres were chopped with a Graco air chop gun to the length of 25mm and mixed manually with the resin to achieve a fibre volume fraction of 30%. In this stage, each pressing charge has been produced by laying parallel cylinder-shaped sub-charges to ensure a homogeneous material distribution. Then, in the second stage of the project, the fibre and the resin were continuously mixed together using a twin-screw extruder that was able to chop the fibre while mixing. This allowed to extrude the right amount of material for each part, facilitating net-shape moulding, and reducing the material waste. Maturing trials of the so mixed compound was initially performed on hot plates and then upscaled using an oven box.

A tool-skin idea was developed to address the requirement to reduce the takt time. Using incremental sheet forming technology (ISF), a steel sheet of metal was gradually formed into the shape of the demonstrator using a round tipped tool, connected to a computer numerical control (CNC) machine and a punch. The tools skin would be used as a material carrier through every stage of the production cell, enabling the decoupling of the cure time from the takt time. The ISF technology offered a cheaper approach, and required less equipment compared to sheet metal forming processes [5].

Figure 2: Bonnet inner tool-skin produced via incremental sheet forming.

The bonnet inner was then re-designed and optimised to minimise the weight. LS-Task and LS-Opt software were used to perform topology optimisation on the bonnet inner design through an iterative process. A design box was initially assigned and constrained where the hinges and latches were positioned in the corresponding mounting areas of the bonnet. Relevant load cases were set, and at every iteration step the elements of the design box were evaluated. If they were judged to not be contributing structurally then they were reduced in thickness, or remove if the thickness fell under a threshold value.

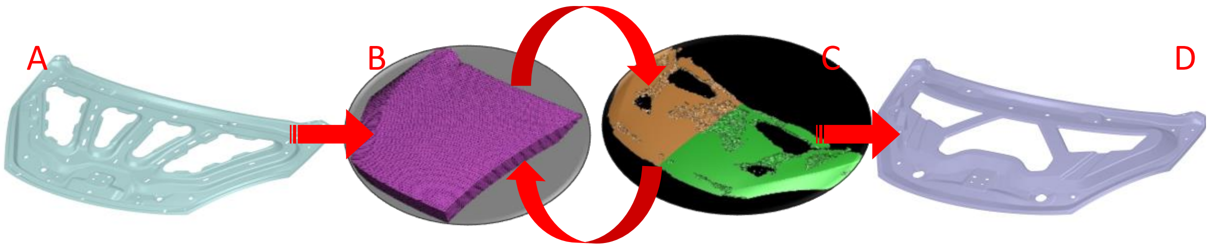

Figure 3 A) Original steel version of the bonnet inner design. B) Design box at the beginning of the iterative topology optimisation process. C) Bonnet inner design after several iterations with some elements reduced in thickness or eliminated. D) Optimised bonnet inner design

Finite element analysis (FEA) was performed to verify that the HiLiTe material and the revised bonnet inner design satisfied the structural integrity requirements. Static torsional load and slam test were modelled considering a full bonnet assembly made of composite inner and steel outer, using LS-Dyna software. For the torsional load case, 50kgf was applied perpendicularly to one of the bump stop locations while the other fixed. The slam test was modelled as the full bonnet was shut at 2.2 m/s.

A life cycle assessment (LCA) was carried out on the final demonstrator design using GaBi software. The purpose of the study was to investigate the impact on the environment of the component produced using the HiLiTe process performing a "Cradle-to-Grave" analysis. The life of the component was divided into three stages, production phase, use phase and end-of-life phase and the potential global warming for each step was modelled with the LCA software against the steel version.

3. Results and discussion

The optimised resin system was proven to cure in a 2-minute cure cycle time prior to a maturing stage of 10 minutes at a controlled medium temperature. The maturing step was found to be the key step to develop the optimum flow during the pressing. Complete mould filling has been achieved with initial mould coverage of 50% in the case of hand mixed charges.

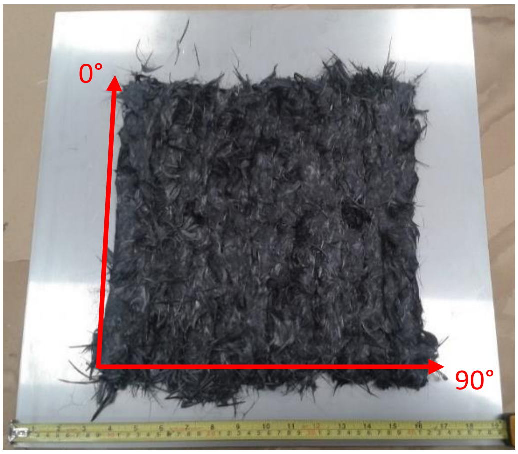

Figure 4: Hand mixed charge of a flat plaque before pressing. The two axes show the longitudinal and transversal material lay-down directions.

Tensile test based on hand mixed materials showed good mechanical properties. However, it was noticed anisotropy in the results. This is thought to be due to the way the charges were prepared, forcing fibres to align along the sub-charges direction. On the contrary, the test performed on coupons machined from plaque produced with material mixed using the twin screw extruder showed no directionality. However, reduced mechanical properties were found in these samples. This has been attributed to an excessive fibre chopping resulting in short fibre length. The barrel size of the twin screw extruder available, 19mm, was considered too small compared to the targeted fibre length, in this case 25mm. The observed effects did not compromise the development of the project but gave indications for further studies. Alternative mixing solution are currently under investigation and will be presented in future publications.

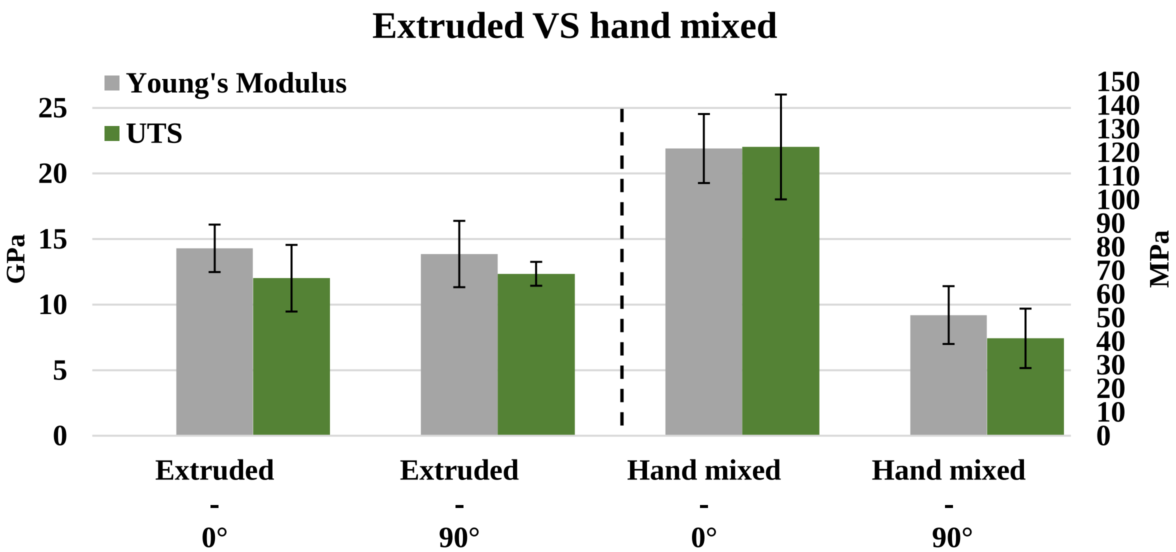

Figure 5: Longitudinal and transversal tensile test performed on flat plaques produced via extrusion, on the left, and via hand mixing on the right.

Coupon specimens treated following a high temperature profile showed increase in the tensile mechanical properties such as Young's Modulus and UTS. The the high temperature process acted has a post-cure cycle. The results are promising for an implementation in production line.

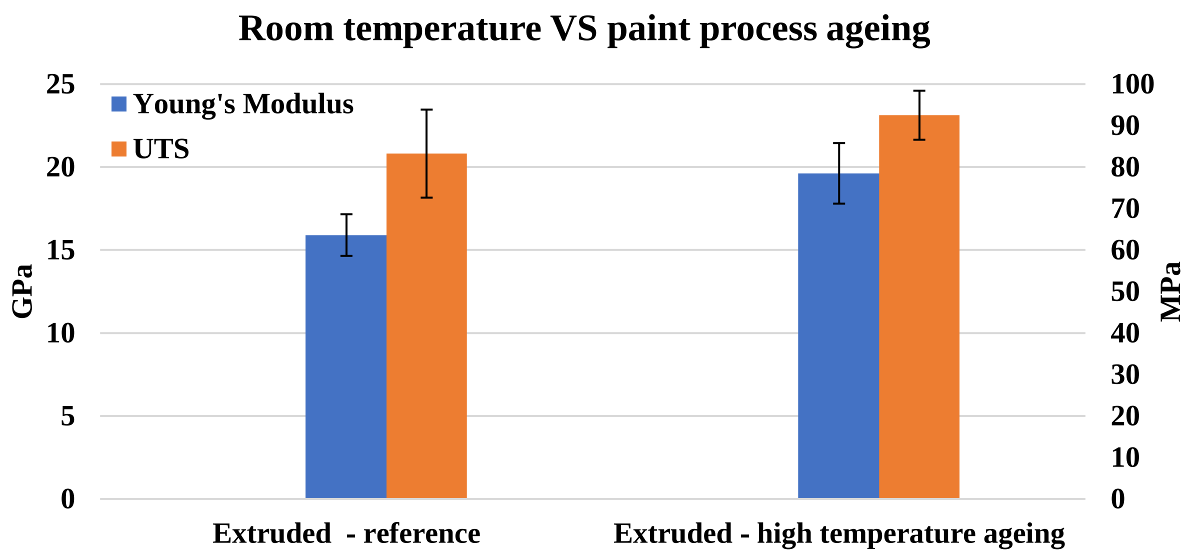

Figure 6: results of tensile test performed on sample machine from plaque produced via extrusion process. The results on the left refer to a group of sample that has not been aged. The results on the right are based on sample that underwent a cycle of 4°C/min ramp from room temperature to 180°C and a 20-minute dwell at 180°C prior testing at room temperature

The bonnet inner produced with the optimised version of HiLiTe material weighed 2663g whereas the initials steel version weighed 4500g. The iterative topology and design optimisation, in conjunction with the use of the HiLiTe material, led to a reduction of 41% in weight, compared to the initial steel version of the bonnet inner, while maintaining or exceeding the structural performance of the equivalent steel structure. The final design has also been modelled using a FE analysis and full-scale demonstrator is currently under testing to correlate/validate the model. The results on the torsional load modelling showed a 10% increase of torsional stiffness using HiLiTe material and the optimised bonnet inner design versus the initial steel version.

The 2-minute takt time for the full production cell has been modelled using Spaceclaim and Algoryx Momentum Software. Due to the limitation of the size of the available extruder, it was assumed the use of three 19mm twin-screw extruder operating in parallel to meet the throughput required for the desired takt time. Future work will include only one mixing device.

The cost estimation analysis showed a 52% reduction, based on commercial available competitors, when compared to traditional composite semi-finish products.

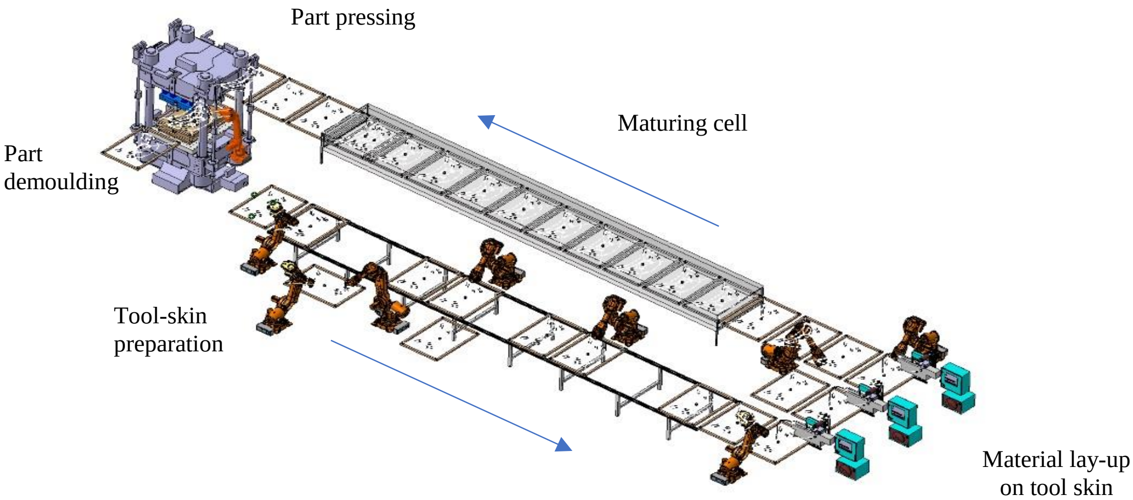

Figure 7: rendering of the HiLiTe production cell

The LCA impact calculations were determined using the international reference life data (ILCD) recommendation methodology. A key difference between the steel and composite models was shown to be during the use phase, where the lighter composite component induces a reduced GWP100 impact than the heavier steel version. A difference of 12.5 kg CO2 between the average total steel GWP100 and the average total composite GWP100 has been found.

4. Conclusion

The 3-year project HiLiTe has been presented in this paper. A novel cost effective end-to-end production process for automotive composite manufacturing has been developed. The weight saving and cost reduction targets have been met, achieving a weight reduction of 41% and cost reduction of 52%. This has been possible through the development of a new material and the optimisation of the component design. The new component design with HiLiTe material has been modelled using FE analysis and the full-scale demonstrator is currently under testing to correlate the model. It has been found that the current mixing approach is not the optimal solution, and an alternative system is currently under investigation. An LCA study assessed the environmental impact of the part through a comparison between the traditional steel component and the optimised composite version produced with HiLiTe material.

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