

AUTOMATED SPRAY DEPOSITION FOR NET-SHAPE CARBON/EPOXY COMPRESSION MOULDING

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SUMMARY

Details are presented of an automated process for manufacturing net-shape charges for compression moulding, using a spray deposition technique. The novel process uses a resin-spray technique to position and hold fibres onto the tool face. The process is intended for producing structural components using discontinuous bundles for medium volume applications.

Keywords: Discontinuous, carbon fibre, spray deposition, compression moulding, epoxy

INTRODUCTION

Discontinuous fibre composites constitute a major proportion of materials used within automotive, marine and aeronautical applications, due to their versatility in properties and relatively low manufacturing costs. Material and processing costs of discontinuous fibre composites can be up to two orders of magnitude lower than for pre-impregnated textile composites and through efficient design, can potentially replace textile composites with no reduction in performance. Crucially, with increasing global composites consumption these materials offer a recycling route for textile composites, with opportunities for subsequent re-use.

Discontinuous fibre composites have become increasingly attractive for structural applications, as material and process advancements have reduced the performance gap between discontinuous and continuous reinforcements. At high volumes (>20,000ppa), moulding compounds have progressed from cosmetic glass/polyester materials to advanced structural derivatives consisting of carbon/epoxy. These materials have been used extensively in the automotive industry [1-3], and more recently in the first aerospace application [4] – offering a 50% weight saving compared with aluminium [5]. Mould design can prove difficult, especially for complex 3D parts, because of the material's high fibre loading. It is important to prevent flow lines forming within critical stress regions, as these can seriously compromise the mechanical properties [6]. High areal coverage of the tool (~95%) is necessary to restrict the amount of flow, but this can inevitably lead to large amounts of touch labour to position the charge.

For medium volumes (1,000-20,000ppa), automated processes have been developed to produce low cost, non-woven fibre preforms for liquid moulding routes. Directed Carbon Fibre Preforming (DCFP) has been developed to eliminate the need for intermediate fibre conversion by processing fibres in their cheapest format [7]. Industrial-grade fibres are chopped directly from the bobbin and sprayed with a powdered binder onto a perforated tool (vacuum table) to create random fibre preforms. Cycle times are approximately 5 minutes for a complex 3D component, which removes the bottle-neck associated with conventional preforming processes. Robotic deposition ensures repeatability and low material wastage (<5%), whilst offering significant cost savings over alternative carbon fibre processes [8, 9].

DCFP has been evaluated for automotive [10], wind energy [11] and aerospace applications [12], where demands for structural performance can be met by introducing aligned fibres in the loading direction. This is typically achieved by mechanical methods, such as a concentrator, to preferentially align the fibres as they fall from the chopper gun. A study by Harper *et al.* [13] indicates that the level of fibre alignment achieved by this method however, is strongly thickness dependent. The perforations in the vacuum tool become blocked with increasing fibre areal density, causing a reduction in holding force and consequently misorientation of subsequent fibres. The level of alignment (fibres between $\pm 10^\circ$) is reported to decrease from 94% to just 23%, as the areal density of the preform increases from 145gsm to 1600gsm.

Historically, manufacturing thick-section and deep-draw parts has been a challenge with DCFP. Firstly, there is a limit to the amount of fibre that can be held in position with the vacuum retention method ($\sim 2000\text{gsm}$), resulting in fibre falling off steep sided tool faces. Secondly, the in-plane permeability of these materials can be an order of magnitude lower than for conventional woven textiles ($0.4 \times 10^{-10} \text{ m}^2$ at just 30% V_f), with inter-preform permeability variability being as high as $\pm 49\%$ [14]. This complicates tool design and can greatly increase part scrap rate.

SCOPE OF PAPER

This paper presents details of a new automated manufacturing process for producing structural, net-shape components from discontinuous carbon fibre bundles. The process combines the spray deposition approach of conventional DCFP with a compression moulding route, eliminating the need for a separate preforming stage. The system offers lower cycle times, high levels of automation, high precision in fibre placement, and low wastage compared with DCFP, contributing to greater cost savings.

Results are presented from an optimisation study, which focuses on maximising the mechanical performance of parts manufactured using the net-shape charge approach. Test coupons are produced on vertical tooling plates to study the level of adhesion provided by the sprayed epoxy. Low speed impact (3.5m/s) and in-plane quasi-static material properties are presented, which are benchmarked against commercial

carbon/epoxy structural moulding compounds. A cost analysis is also presented for a structural automotive component.

MANUFACTURING PROCESS

Bentley Motors Limited has installed a research-scale discontinuous carbon fibre manufacturing facility at the University of Nottingham, under the RayCell project. The development of a novel powder matrix system has enabled a shift away from liquid moulding towards low-flow compression moulding for structural discontinuous fibre composites. A B-staged, epoxy powder is sprayed simultaneously with chopped fibres to create a net-shape charge. The powder is delivered in an air-stream through the centre of a prototype propane burner, attached to the arm of a 6-axis robot, as shown in Figure 1. The powder is activated by the burner and delivered as a mist to adhere the fibres in position, rapidly solidifying on contact with the rigid mould tool. The result is a net-shape charge with 100% tool coverage. The cycle is completed by curing the charge under heat and pressure in a matched-sided tool.

Fibres are cut to length using a carbon fibre-specific chopper gun, using a rotating blade design. The propane burner attaches to the exit nozzle of the chopper gun to ensure that the fibres and powder resin are pre-mixed before entering the delivery tube of the burner. Powder is delivered to the burner through an Ø8mm anti-static hose using a specially commissioned double-venturi pump. The pump provides smooth and controlled delivery of the powder to the burner, which is particularly important for low melting point polymers because pulsing can cause ignition. The powder is stored in a fluidising chamber and is siphoned into the pipe by the first (feed) venturi. The second venturi is located at the burner end of the pipe, which controls the material delivery rate into the burner and ensures the powder particles are uniformly distributed within the tube.

Pencil-type burners are housed within a shroud, which converges around the exit of the delivery tube (see Figure 1a) to concentrate the flow of hot air into the path of the powder stream (Figure 1c). The residence time of the powder in the heating zone must be sufficient to melt all of the particles, but the velocity of the supply must be greater than the rate of combustion of the feedstock powder. A pressure and flow regulated supply of cool air provides a curtain between the low melting temperature polymer feedstock and the flame to prevent ignition. The temperature of the burners can be adjusted to suit the flow rate of powder by regulating the air/fuel mixture and also increasing the cooling air flow within the shroud.

High charge coverage not only facilitates the use of a high viscosity resin, but also ensures that the integrity of the reinforcement is maintained during compression. Restricting material flow prevents bundle fragmentation and also prevents the fibres becoming misaligned along flow lines. This enables greater precision for fibre placement and the opportunity to produce highly aligned, long fibre composites using the mechanical methods outlined in [13]. The powdered resin is only required to flow a relatively short distance through the thickness of the moulding, compared with the in-

plane flow of liquid resins, greatly reducing the likelihood of dry spots in large complex parts.

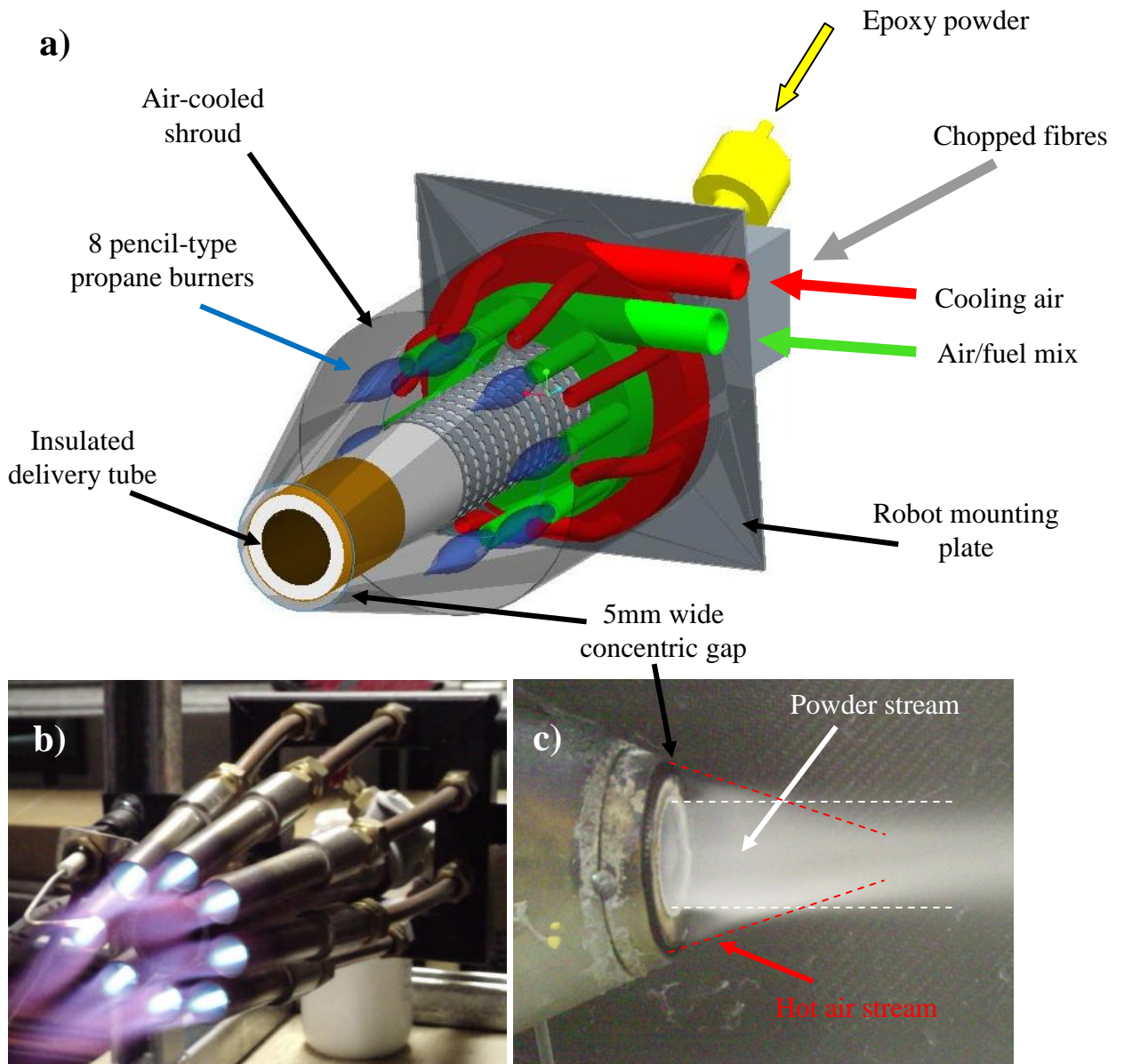


Figure 1: (a) Propane-fuelled burner. (b) Outer shroud removed to show ignited burners. (c) Tip of burner indicating how hot air stream converges with powder delivery stream.

The propane burner offers a single-shot process, reducing cycle times by approximately 50% compared with conventional spray preforming (Figure 2). The charge is deposited directly into the compression mould tool, eliminating the preform consolidation, cooling and transfer stages. Capital costs are also reduced by obviating the need for separate mould and preform tools. Part thickness is no longer a limiting factor and more challenging geometries with deeper draw can be considered. Initial trials indicate that moulding pressures of just 10bar are required to achieve fully impregnated laminates

when adopting this process, yielding volume fractions of up to 50%. These are considerably lower than pressures typically used for high-flow SMC moulding (40-100bar), enabling an autoclave to be used with low cost single sided tooling for large structures.

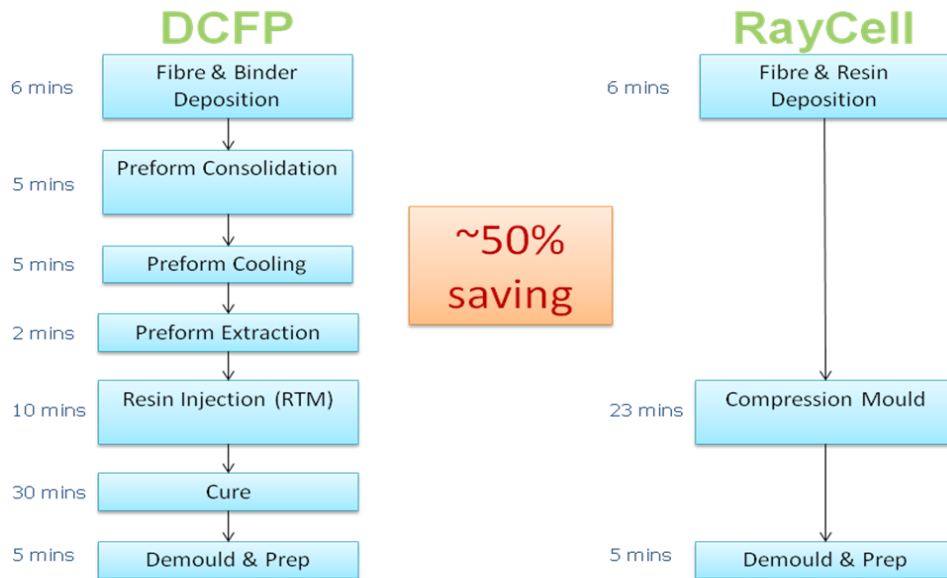


Figure 2: Flow chart indicating the cycle time savings for the RayCell process compared with conventional DCFP

POWDERED RESIN CHARACTERISTICS

The powder is a proprietary blend of epoxy resins and curatives formulated by Hexcel, Duxford, UK. The constituents are pre-mixed to produce a homogeneous fluid, before being extruded, rapidly cooled and then finally ground into a fine powder (99% particles <120µm). The result is a material that provides good flow characteristics at room temperature without sintering, making it suitable for conveying over long distances in Ø8mm pipe. The cured material properties are comparable to a commercial toughened epoxy prepreg system, commonly used for high performance automotive applications. However, cure times are significantly shorter than for prepreg, taking just 23 minutes to achieve full cure at 125°C. Components can be hot demoulded from the tool, with the capability to post cure to achieve a T_g of over 180°C to endure automotive painting cycles.

Studies using a Differential Scanning Calorimeter indicate that typically, only 11% of the cure enthalpy is utilised as the powder is processed through the propane burner, facilitating the two stage heating process. Low viscosities (<10Pas at 125°C) during the secondary heating stage enable good fibre impregnation and minimum void content, as shown by Figure 3. Grey scale analysis indicates that the void level is approximately 1.6% by volume for the sample shown.

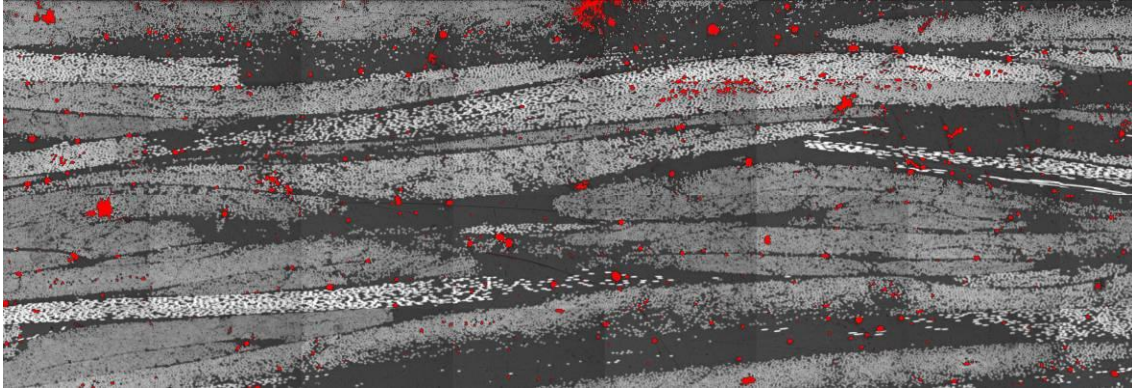


Figure 3: Optical micrograph of specimen cross-section, produced by the RayCell process. Specimen is 3.75mm×1.65mm. Grey scale analysis indicates that the void level is approximately 1.6% by volume (shown in red).

MATERIAL CHARACTERISATION

RayCell Specimen Preparation

Laboratory scale test plaques were manufactured on the research facility at Nottingham, by depositing a fibre/resin charge onto a vertical prepreg tool. This configuration was chosen because it was considered to be the most challenging geometry for future applications. Fibre and resin was deposited along linear spray paths, each offset by 50mm, initially moving in an east to west motion, followed by a north to south motion. This orthogonal strategy has previously been proven to minimise areal density variation by 30% compared with a single east to west motion [15]. A fibre length of 37mm was selected using 12K T700 50C carbon fibre supplied by Toray. Deposition rates of 165g/min and 195g/min were achieved for the resin and fibre respectively during these initial trials, although the current burner has been designed to activate a maximum of 1kg/min of epoxy powder. Fibre and resin wastage levels were measured to be 2.5% and 10% of the total mass of each constituent sprayed. These values reflect the amount of fibre that did not adhere to the tool during spraying and the amount of powder that was not activated as it passed through the burner.

Once deposition was complete, the 500mm×500mm tool was loaded into a press at a temperature of 125°C to cure the charge. A pressure of 10bar was used to produce a plaque with a fibre volume fraction of 43% and a thickness of 4mm. A pinch pressure of 2bar was applied during the first 3 minutes to allow the resin to reach its minimum viscosity; ensuring fibres were fully impregnated and preventing bundle fragmentation from occurring.

Material Properties

A range of experimental tests have been conducted to benchmark the mechanical performance of the RayCell material against the DCFP/RTM materials presented in [13]. In addition, manufacturers' data for a selection of commercial carbon fibre moulding compounds is included for comparison. All results have been normalised to a fibre volume fraction of 50%.

Figure 4 shows a comparison of tensile stiffness and strength for all of the discontinuous carbon fibre materials. In general, the RayCell material competes very well against the more established DCFP material and the commercial moulding compounds. The tensile stiffness (50GPa at 50% V_f) is higher than both random DCFP materials, ASMC and HexMC. It is only outperformed by the MS-4A material, produced by YLA Inc, although it is unclear whether this value is isotropic or influenced by flow induced alignment because the tensile specimens were moulded net-shape. The tensile strength of the RayCell material (198MPa at 50% V_f) is consistent with the DCFP plaques, given the difference in carbon tow size, but is on average 20% lower than all of the commercial SMCs. This can be partially attributed to preferential fibre alignment in the Lytex 4149 and MS-4A materials, but also because aerospace grade fibres are typically used (3K fibres in the Lytex 4149) rather than the T700 12K tow used for the RayCell material. The tensile strength of these heterogeneous materials is strongly thickness dependent [4], but thickness data is unavailable for many of the materials presented, making it difficult to make direct comparisons.

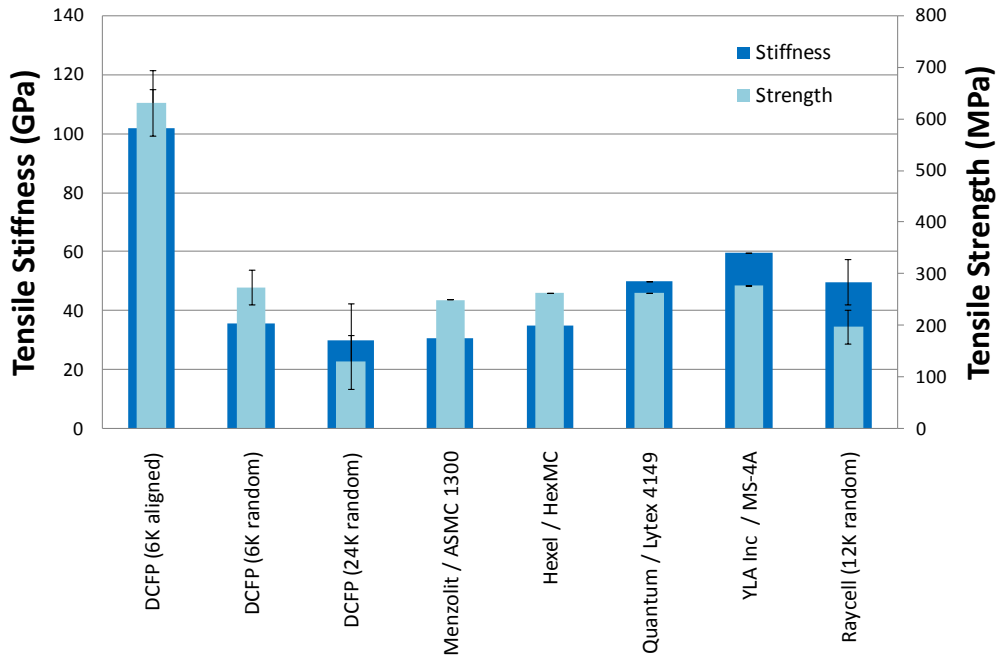


Figure 4: Comparison of RayCell tensile properties against a range of commercial carbon SMCs and DCFP (values taken from [13]).

Three point bend tests were also performed for the RayCell material and the results (not shown) were compared with manufacturers' data for the carbon SMCs. A flexural stiffness of 27GPa ($\pm 9\%$) and a flexural strength of 484MPa ($\pm 7\%$) was achieved. In general, the trend observed compared with the commercial systems was similar to the tensile test results. The RayCell material was outperformed by the Lytex 4149 and MS-4A materials, which on average exhibited 40% higher flexural stiffness and 20% higher flexural strength due to suspected fibre alignment. The flexural properties of the RayCell material were however, comparable with the Menzolit ASMC 1300 material (28GPa, 516MPa for flexural stiffness and strength respectively).

“Normal Flatwise” flexural Charpy impact tests were performed using a strike velocity of 3.46m/s. The results from this test provide a comparative quantitative measure of toughness, indicating the energy required to fracture each material. Figure 5 shows a comparison of impact strength for the RayCell material and two commercial carbon SMCs. A similar trend is observed to the tensile results, where the impact strength of the RayCell material (83kJ/m^2 at 50% V_f) is within the 67kJ/m^2 to 87kJ/m^2 range of the commercial systems.

The aligned DCFP data presented in Figure 4 demonstrates the potential for increasing the mechanical performance of the RayCell material to compete with continuous fibre systems. This projected increase in properties is considered to be conservative, because unlike DCFP, the level of fibre alignment achieved by the RayCell process is thickness independent. This presents a unique opportunity for creating tailored fibre architectures for structural applications, something that is largely impossible with conventional compression mould charges.

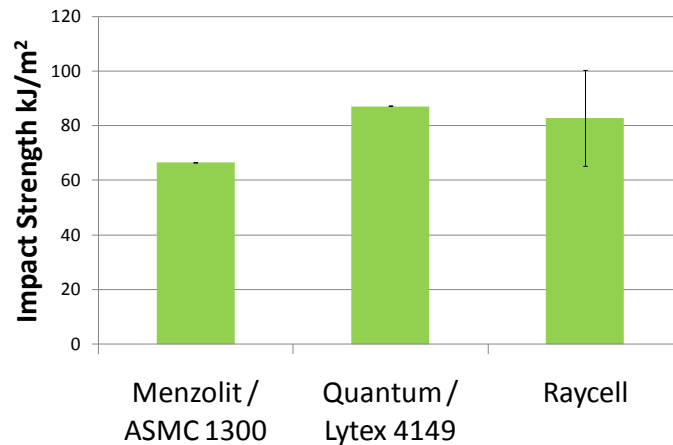


Figure 5: Comparison of Charpy Impact Strength for RayCell material and two commercial carbon SMCs at a fibre volume fraction of 50%. Tests performed to EN ISO 179-1:2000.

COST MODELLING

A generic parametric event-driven cost model [9] has been used by Bentley Motors Ltd to anticipate the production costs of a structural component using RayCell, resin transfer moulding and prepreg. The model has been used to examine various levels of automation to optimise part cost at various projected annual production levels. The model simulates the manufacturing process by splitting it into a number of steps and assigning materials and labour input at that step together with relevant tooling and capital equipment. Sensitivity analysis is a powerful feature of such a model and allows assessment of varying material, labour and tooling costs as well as comparison of process alternatives.

Figure 6 summarises component cost as a function of production volume for the three moulding routes under consideration. RTM Light is shown to be the most economical

process between volumes of 100ppa to 1,000ppa. Reduced levels of intermediate processing ensure that the material costs are 46% lower than prepreg and layup times are 50% shorter. The capital investment required for RTM Light is 67% lower than for RayCell when amortised over this volume range.

The target production volume for the component considered is 4,500 parts per annum. Figure 6 demonstrates that the RayCell process becomes the most economical route beyond a production volume of 1,100ppa. Figure 7 shows a breakdown of costs at 4,500ppa, which indicates that RayCell is 64% lower than prepreg and 31% lower than RTM Light. The major advantage of RayCell at this volume are low material costs, which are 63% lower than the prepreg because industrial grade 12K fibres are used directly from the bobbin without incurring any added value. Material efficiency levels are also much higher for RayCell: 95% and 80% for fibre and resin respectively, compared with 70% (combined) for prepreg and 80% (combined) for RTM Light. The efficiency values for RayCell are expected to increase during further process optimisation, further reducing material costs. Manufacturing costs are 67% lower than for prepreg due to low levels of touch labour through automation and short cycle times. It is estimated that it is possible to layup the RayCell part in just 6 minutes, compared with 180 minutes for prepreg and 90 minutes for RTM Light. High capital expenditure is the only disadvantage to the RayCell process compared with the other two processes. However, at just 20% of the part cost (£76/part) this can be supported at this production volume, but not at annual volumes below 1,100.

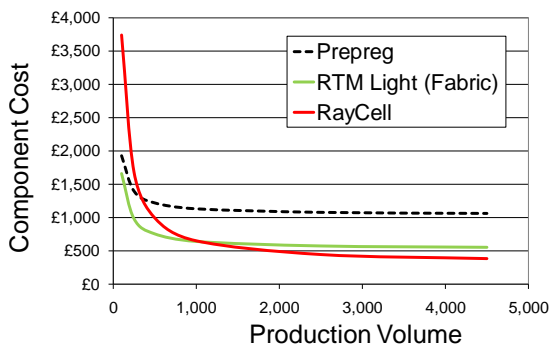


Figure 6: Component cost as a function of production volume

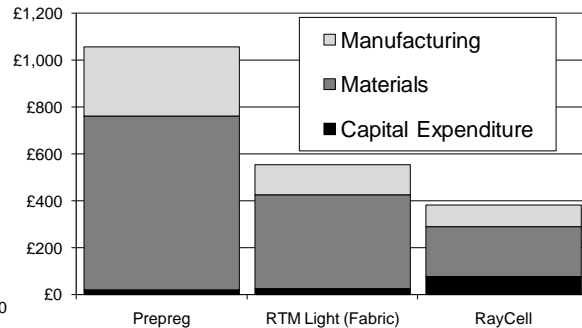


Figure 7: Component cost breakdown for production volume of 4,500ppa

CONCLUSIONS

Details of a novel automated manufacturing process have been presented for producing net-shape charge material for low-flow compression moulding. The process enables controlled delivery of random and highly aligned fibres to produce tailored fibre architectures for structural applications. Preliminary mechanical testing of random fibre plaques has shown that the tensile, flexural and impact strengths are comparable with commercial carbon fibre moulding compounds. Cycle times are estimated to be 50% shorter than for conventional Directed Fibre Preforming/RTM routes and part costs

have been demonstrated to be 65% lower than prepreg for a case study requiring 4,500ppa.

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