FLOW CHARACTERISTICS OF CARBON FIBRE SHEET MOULDING COMPOUNDS

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ABSTRACT

This paper presents the development of a low cost carbon fibre moulding compound using a robotic spray deposition process, developed at the University of Nottingham. Directed Fibre Compounding (DFC) produces a net-shape charge pack from virgin carbon fibres and a low cost liquid epoxy. The resin is heated to minimise the viscosity, ensuring good dispersion and wet out of the chopped fibres during the deposition stage. The charge is then chemically B-staged to avoid fibre/matrix separation during compression moulding.

The aim of this study is to understand the moulding characteristics of this new material, compared with an equivalent carbon fibre/epoxy compound produced using a modified glass SMC production facility. Two commercial CF-SMC benchmarks are also considered. The influence of charge size (percentage mould coverage) on mechanical performance has been studied. Results indicate that high levels of flow can be achieved for the DFC material without encountering fibre/matrix separation or introducing voids. This level of flow has a positive effect on both the longitudinal tensile stiffness and strength, due to flow induced alignment. However, intra-plaque variability increases, highlighting the advantages of adopting a net-shaped DFC charge.

1 INTRODUCTION

Compression moulding offers one of the fastest routes for manufacturing composite components from thermoset matrices, making sheet moulding compounds (SMC) the most widely adopted application of fibre reinforced composites within the automotive industry [1]. The majority of these materials are derived from chopped glass rovings and filled polyester resins, with limited composite stiffness (<15GPa) and strength (<100MPa) at low fibre volume fractions (<20%).

A number of leading SMC manufacturers have exploited higher stiffness carbon fibres (CF), producing advanced SMCs that are 300% stiffer than E-glass derivatives. The cycle time for these materials is commonly 5-45 minutes, depending on part thickness, which is suitable for production volumes approaching 100,000ppa. However, CF-SMC has remained largely unexploited due to the high cost of raw materials and the cost of intermediate processing. CF-SMC has been developed in the aerospace industry from chopped unidirectional prepreg to ensure good fibre wet-out and fire safety properties, suitable for cabin, cargo and other interior parts [2]. This material uses a highly viscous prepreg resin system to help avoid fibre/matrix separation, but this inhibits excess flow during moulding. This type of CF-SMC is therefore analogous to a discontinuous fibre prepreg, requiring high percentage tool coverage due to limited flow capability. Alternative CF-SMCs are produced using more traditional SMC manufacturing routes, depositing and pressing chopped fibres onto a resin film [3]. Commercial products of this type tend to use vinyl-ester matrices to reduce cost and enable greater in-mould flow compared with the epoxy derivatives. In-mould flow is beneficial for producing integrally stiffened SMC components, for incorporating features such as ribs. However, it is important to understand the flow characteristics, as it can result in anisotropic mechanical properties and increased volume fraction variation [4, 5]. The adhesion between carbon fibre and vinyl-ester however, can be poor compared with carbon/epoxy, limiting mechanical performance [6, 7].

This paper investigates a new process for producing low cost carbon fibre/epoxy SMCs, which are capable of high levels of flow to facilitate a 5 minute cycle time. An alternative fibre wet-out technique is investigated, rather than deriving CF-SMCs from expensive prepreg. Directed Fibre Compounding (DFC) is a new process developed at the University of Nottingham to produce carbon fibre/epoxy charge packs for isothermal compression moulding. DFC is an automated process that simultaneously deposits virgin carbon tows and a low cost liquid epoxy onto a tool surface. The low resin viscosity ensures a high level of tow impregnation during spraying, minimising the risk of voids during compression moulding.

A range of material and process related parameters have been studied to understand their influence on the level of flow achievable. Mechanical properties are presented for a range of charge sizes (initial percentage mould coverage) for a 1-dimensional flow scenario. These are compared against two commercial CF-SMC benchmarks, a carbon fibre /epoxy SMC (designated EP-SMC) derived from chopped unidirectional prepreg and a carbon fibre /vinyl ester SMC (designated VE-SMC) produced by traditional methods, pressing fibres into a resin film. Data is also presented for a third carbon fibre moulding compound produced at the University of Exeter. This material uses the same carbon fibre/epoxy as DFC, but was produced using a modified glass SMC production facility. Carbon rovings were chopped and then distributed onto a resin film, which was then squeezed through the fibres. A charge pack was cut from the sheet material before compression moulding. This process is referred to as Press Formed Compounding (PFC) during this study.

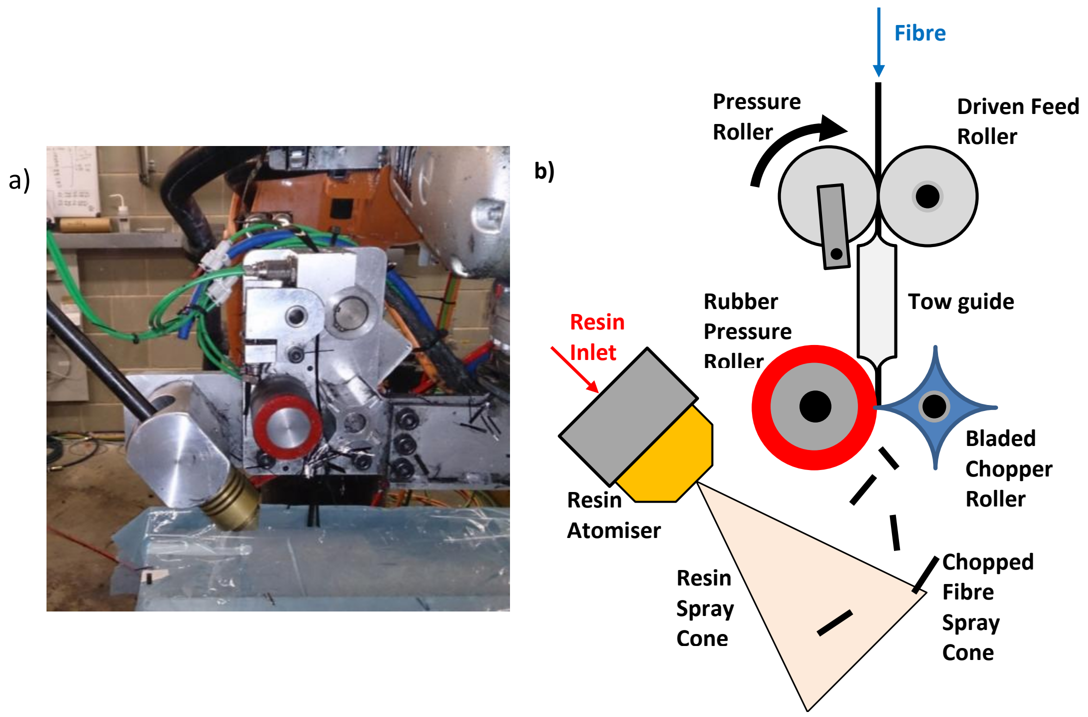


Figure 1: University of Nottingham DFC end effector fitted to robot arm, photo (a) and labelled schematic (b) of end effector

2 EXPERIMENTAL PROCEDURE

DFC is a development of the Directed Carbon Fibre Preforming (DCFP) process [8-10]. Both produce net-shaped, discontinuous fibre materials via robotic spray deposition, with low material wastage (< 3% by mass). However, a liquid resin is sprayed during the fibre deposition stage of DFC to produce a compression moulding compound, minimising the risk of large dry regions in the final component. The robotically-controlled spray path is optimised to ensure uniform fibre distribution and to achieve fibre volume fractions up to 55%. A key advantage of DFC is that complex geometries can be formed by adjusting the spray path, with no significant effect on cycle time. It is therefore possible to produce 3D charge packs, sprayed either directly onto a mould surface or assembled in stages. This provides the opportunity to combine the discontinuous fibre architecture with other fibre formats to produce a hybrid structure.

Figure 1 shows the robot mounted chopper. The carbon tow is fed into the chopper via a driven feed roller and then guided into the chopper roller. A cone of randomly orientated chopped fibres is sprayed towards the tool surface, where the fibre length can be controlled on the fly by adjusting the ratio of the feed and chopper roller speeds. An atomised cone of liquid resin converges with the stream of fibres at the tool surface, wetting the fibre bundles individually as they are deposited. The resin is pre-heated to minimise the viscosity, ensuring good dispersion and wet-out of the chopped fibres. The charge is chemically B-staged to increase the viscosity before compression moulding.

DFC and PFC materials have been produced from the same carbon fibres and epoxy resin for this study. The fibre was Toray T700, with a tow size of 12K and 1% sizing. This level of sizing is suitable for achieving consistent fibre chopping. The epoxy resin is a formulated system from Huntsman: Resin XU 3508, Aradur 1571, Accelerator 1573 and Hardener 3403. One of the key features of this system is the opportunity to B-stage, partially curing it at room temperature once mixed. Consequently its viscosity increases, enabling it to be more easily handled and stored for a short period, whilst reducing the risk of fibre/matrix separation during compression moulding. When the temperature is elevated during moulding, the second hardener activates to complete the cure cycle.

The EP-SMC uses UD prepreg chopped into 50mm×8mm chips and is deposited randomly to form a sheet compound. It has a snap curing resin which can be moulded in 2 minutes and is suitable for automotive applications. Achieving a high Tg of 125°Cenables parts to be hot demoulded.

The VE-SMC is produced by conventional glass compounding methods. Carbon fibres are chopped to 25mm and the matrix system has a continuous service temperature of 170°C, making it compatible with the E-coat process commonly used in the automotive industry.

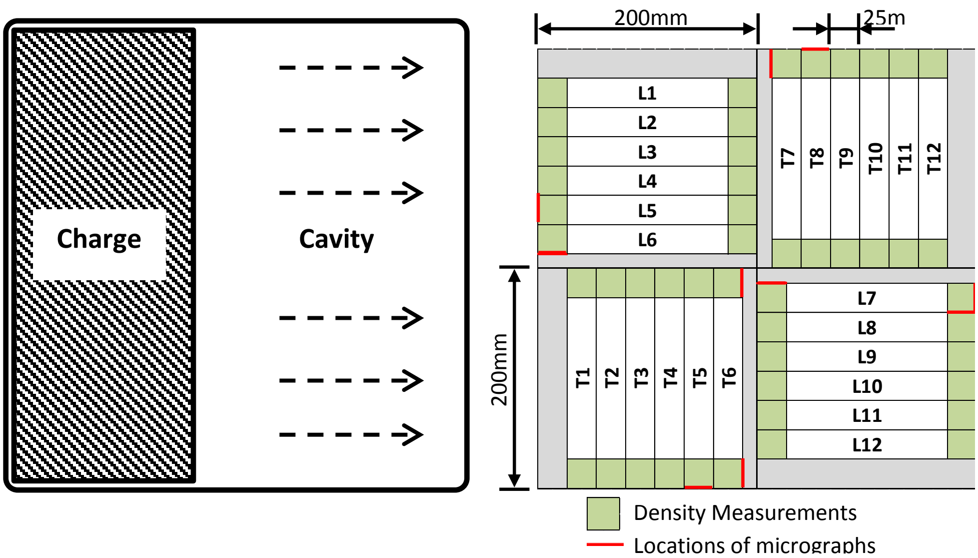


Figure 2: Initial charge position and cutting plan for the 405mm x 405mm plaques. Locations for tensile coupons, density measurements and micrograph shown.

A flat compression mould tool was used to produce plaques for tensile testing. The cavity was 405mm×405mm×3.2mm and a tool closure speed of 1mm/s was used throughout. DFC and PFC were moulded isothermally at 130°C for 30minutes, followed by a 3.5 hour freestanding post cure in an oven. All moulding parameters for the commercial SMCs were taken from their datasheets.

Plaques were produced for all materials using two charge coverage strategies; 50% and 100%, to show the influence of flow. EP-SMC however, was moulded at 80% according to the manufacturer's recommendation. Moulding pressure, percentage mould coverage and fibre length were all varied further for the DFC process. A rectangular charge was used for all plaques with an initial mould coverage of less than 100%. This encouraged the flow to be one-dimensional, providing suitable regions to take test coupons from both the original charge region and the flow region (see ***Figure 2***). Twelve tensile specimens were tested at two orientations for each plaque. ***Figure 2*** also indicates micrograph locations, used to observe fibre bundle waviness, void content and the influence of fibre-tool interactions.

3 RESULTS AND DISCUSSION

3.1 Comparison between DFC and other Carbon-SMC

A comparison of tensile properties is presented in ***Figure 3*** for all of the moulding compounds investigated. The red dotted line indicates average values for the 100% DFC plaque, which were 36GPa and 320MPa for stiffness and strength respectively at a moulded fibre volume fraction of 50%.

There was less than 3% variation between the longitudinal and transverse properties for the 100% DFC material, and error bars were small (<8%) confirming that the material is homogeneous and isotropic when moulded net shape. The longitudinal properties increase for smaller charge sizes (50%), indicating flow induced alignment. The error bars remain low however, indicating good levels of fibre dispersion during flow. The properties of the DFC material are competitive against the commercial systems. The stiffness of the 100% DFC is comparable to the prepreg derived EP-SMC material, accepting there has been some fibre alignment in the commercial material due to the 80% initial charge. The stiffness of the 100% DFC is ~20% higher than the stiffness of the 100% VE-SMC and 40-45% higher than the 100% PFC material. Furthermore, the strength of DFC is significantly higher than the other materials. The average ultimate strength for the 100% VE-SMC material is 90MPa, 72% lower than DFC. This can be attributed to the poor interfacial bonding between the vinyl-ester matrix and the carbon fibre. The properties for the PFC material are comparable with the commercial VE-SMC material, for both charge sizes investigated. Both materials are derived in the same way by pressing chopped fibre bundles into a resin film. However, the PFC material failed to fully wet-out the fibre bundles.

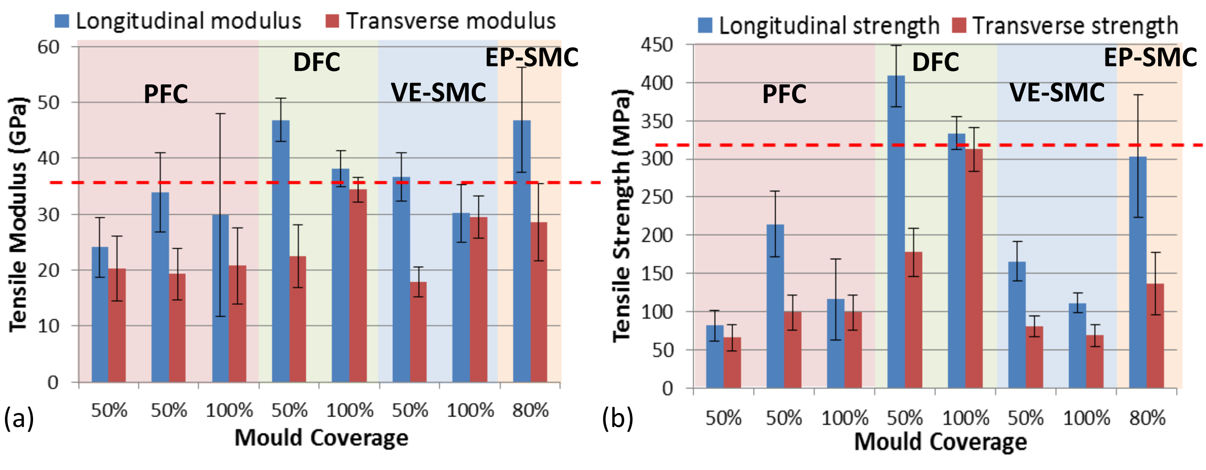


Figure 3: Tensile modulus (a) and tensile strength (b) as a function of mould coverage. All materials moulded at 85 bar.

Fracture sites for each material have been captured in ***Figure 4***. ***Figure 4c*** shows intact fibre bundles at the failure site for PRC, indicating that cracks propagated around the fibre bundles. This was evident across all PFC specimens and suggests that failure was matrix dominated. The fracture site for the 100% DFC coupons is relatively straight, perpendicular to the applied tensile load (see ***Figure 4a***), indicating a fibre-dominated failure. This was observed for both longitudinal and transverse coupons, due to the high level of isotropy. The average filament count per bundle was lower for the DFC material compared with PFC, due to bundle fragmentation during spray deposition. A more homogeneous fibre distribution reduces the potential for resin rich zones, causing a change in failure mode. Flow induced alignment in the 50% DFC coupons resulted in a combination of interface and fibre dominated failures, particularly in the transverse direction (***Figure 4b***). Cracks at the interface propagated along the length of bundles at a lower stress than required to break the fibres, resulting in a matrix-dominated failure.

DFC demonstrates the potential mechanical properties that can be achieved for PFC, if the processing parameters are optimised to improve bundle impregnation. The tensile strength and stiffness of PFC are 67% and 30% lower respectively than DFC.

a) c)

b) d)

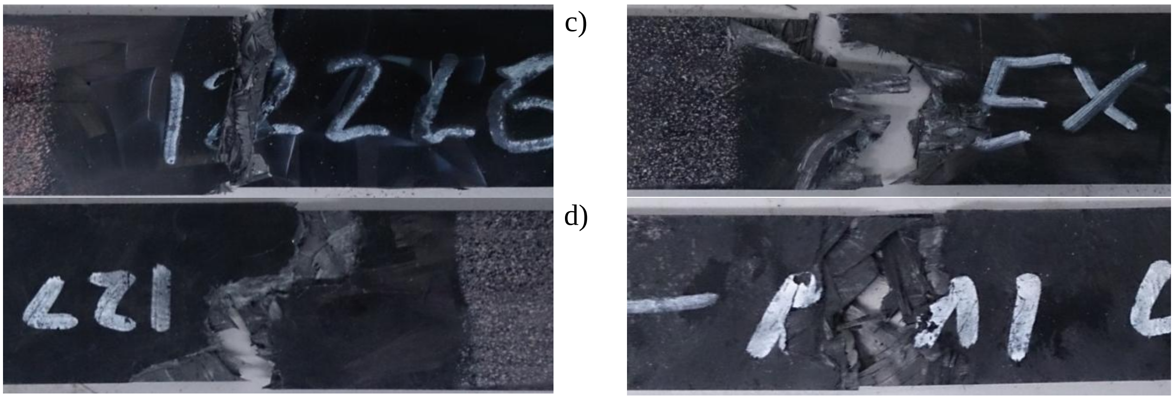


Figure 4: Typical failure mechanisms experienced during tensile failure of longitudinal specimens of (a) net-shape DFC, (b) 50% mould coverage DFC, (c) net-shape PFC and (d) and net-shape VE-SMC

3.2 Effect of Degree of Flow

In-mould flow of the DFC moulding compound causes the discontinuous fibre bundles to rotate and align in the flow direction. This causes a disparity in mechanical properties between the longitudinal (parallel to flow direction) and transverse (perpendicular to flow) directions. The level of flow is dependent on the initial size and shape of the DFC charge and therefore the mechanical properties can be tailored to some extent by encouraging charge flow, as shown in ***Figure 5***. There is a clear linear trend between tensile stiffness and mould coverage, for both the longitudinal and transverse coupon directions. At 100% mould coverage, the stiffness can be considered to be isotropic, at an average value of 34.3GPa for a fibre volume fraction of 45%. As the mould coverage is reduced to 40%, the longitudinal stiffness increases to 42GPa and the transverse stiffness reduces to 21.8GPa. There is no measurable increase in coefficient of variation, indicating homogeneous distribution of fibre.

The tensile strength (***Figure 5b***) exhibits a similar general trend, increasing longitudinally and decreasing transversely as the mould coverage decreases. However, the longitudinal strength is lower than expected for the low coverage plaques (40% and 60%), which can be attributed to an increase in out-of-plane fibre waviness with increased flow. This waviness is mostly observed in the edge regions of the plaque, as shown in ***Figure 6***. The highest degree of waviness is found in the 40% mould coverage specimens (***Figure 6a***), which decreases as the level of in-mould flow decreases. The fibre bundles in the 100% mould coverage plaque are relatively planar (***Figure 6d***). These micrographs also confirm that the filaments remain in bundle form during flow and there are no matrix rich regions caused by fibre/matrix separation.

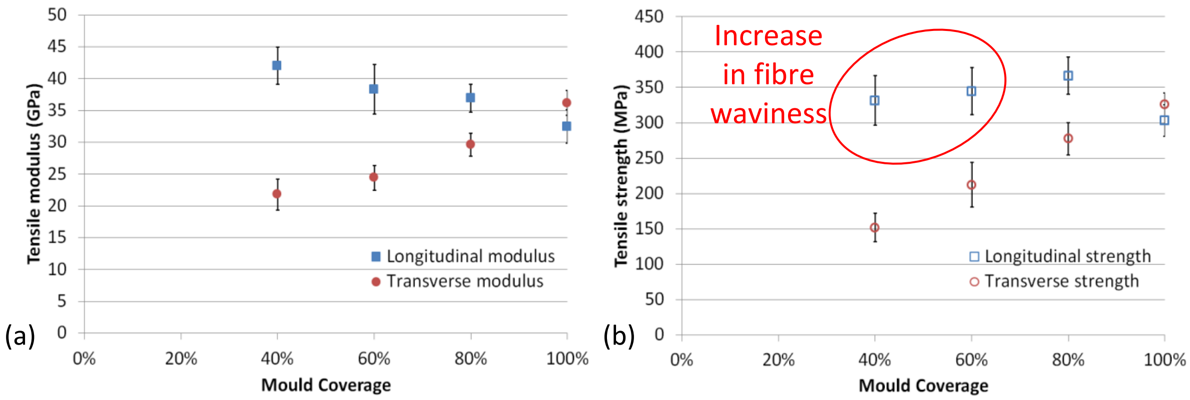
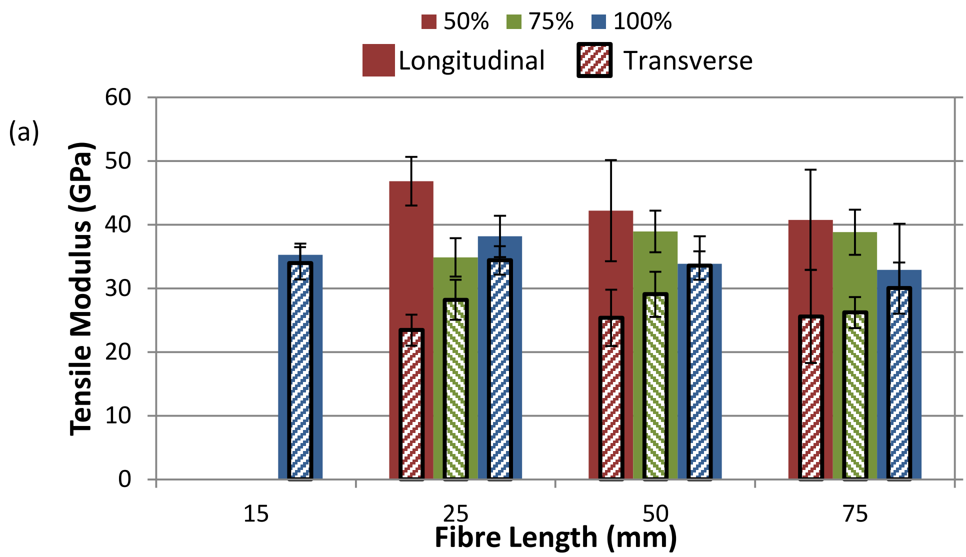


Figure 5: Tensile modulus (a) and strength (b) of DFC plaques. (25mm fibre length, 45% Vf)

Figure 6: Micrographs (5x magnification) of the right hand edge, end of flow, for 40% (a), 60% (b), 80% (c) and 100% (d) mould coverages. All images are parallel to the flow direction

3.3 Effect of Fibre Length

DFC plaques with different fibre lengths, ranging from 15mm to 75mm, were manufactured at a fibre volume fraction of 50%, using 100% charge coverage. It is difficult to establish a trend between the tensile properties and increasing fibre length due to the coefficient of variation. ***Figure 7*** implies that 25mm is the optimum fibre length for 100% mould coverage, yielding the highest tensile stiffness and strength. However, all other data points are within one standard deviation, so the statistical significance of this trend is low. There is however, an increase in the coefficient of variation as the fibre length increases, which can be attributed to the size effect caused by the constant 25mm width of the tensile coupons.



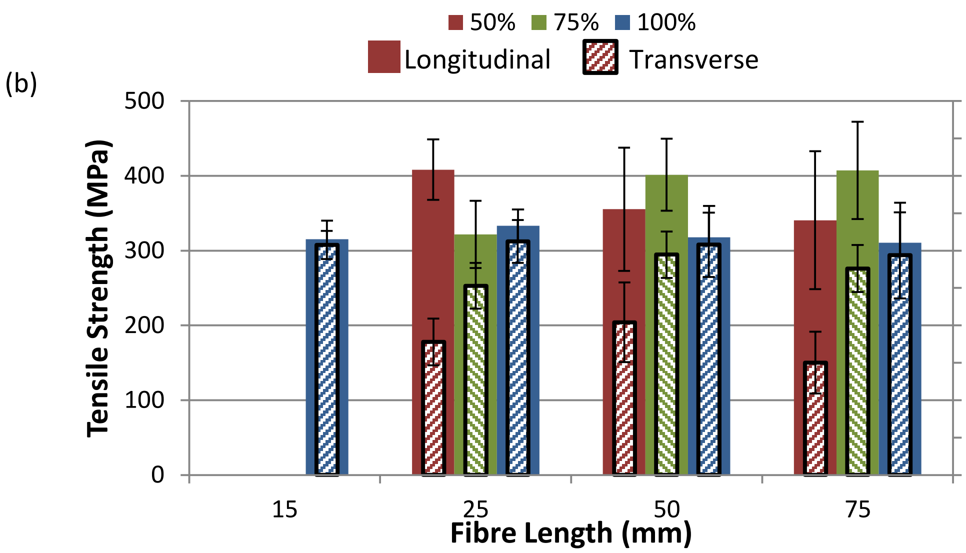


Figure 7: Effect of fibre length on tensile modulus (a) and tensile strength (b) for DFC compounds with 50%, 75% and 100% mould coverages (50% Vf).

The effect of fibre length becomes more pronounced as the charge coverage decreases and the level of flow increases. ***Figure 7*** indicates that the ratio between longitudinal and transverse properties generally increases as the fibre length decreases for smaller mould coverages. Shorter fibres are more susceptible to flow induced alignment than longer (75mm) fibres, which is more prominent for smaller initial charges (50% compared with 100%). However, compounds manufactured using 15mm long fibres did not exhibit acceptable levels of flow during moulding, as large dry patches formed. Chopping fibres shorter increased the level of natural filamentisation, effectively reducing the filament count per fibre bundle [9]. This consequently increased the loft of the compound, increasing the compression forces required to close the mould tool [8]. The number of fibre-fibre interactions increase with shorter fibre lengths, increasing the frictional forces between the fibres, preventing fibre flow [11].

According to ***Figure 7b***, the highest strength for the 50mm and 75mm fibre lengths is achieved when selecting a 75% charge size, compared to 50% charge for the shorter 25mm fibre length. This can also be attributed to fibre waviness. The longitudinal strengths of the 50mm and 75mm fibre length (50% coverage) plaques are theoretically low, as the ultimate strength is limited by the degree of out-of-plane waviness, as previously shown in ***Figure 6***. This is supported by the trend observed for the transverse strength, which consistently decreases with decreasing charge size.

3.4 Effect of Moulding Pressure

Plaques were initially manufactured using 100% charge coverage to isolate the effects of moulding pressure from fibre flow. ***Figure 8a*** shows that there was a reduction in both tensile stiffness and strength when the pressure was reduced from 85bar to 60bar. No further reduction in properties was observed however, when the pressure was reduced to 20bar. Reducing the moulding pressure influences the void content. There are three requirements to achieve complete dissolution of trapped air: 1) high pressure, 2) high (local) flow rate and 3) low initial gas concentration [12]. During compression moulding of net-shaped compounds, the flow is almost negligible and the gas concentration is uncontrolled as a result of the atomisation stage of the liquid resin. Therefore, moulding pressure is the most influential factor controlling the level of voids and higher pressures are required to collapse any air pockets and encourage microscale resin flow. ***Figure 8b*** confirms that the void content is higher (1.5%) for plaques moulded at 20bar, compared with those moulded at 85bar (1.0%). This directly influences the tensile strength, which decreases by 15% when the pressure is reduced from 85bar to 20bar.

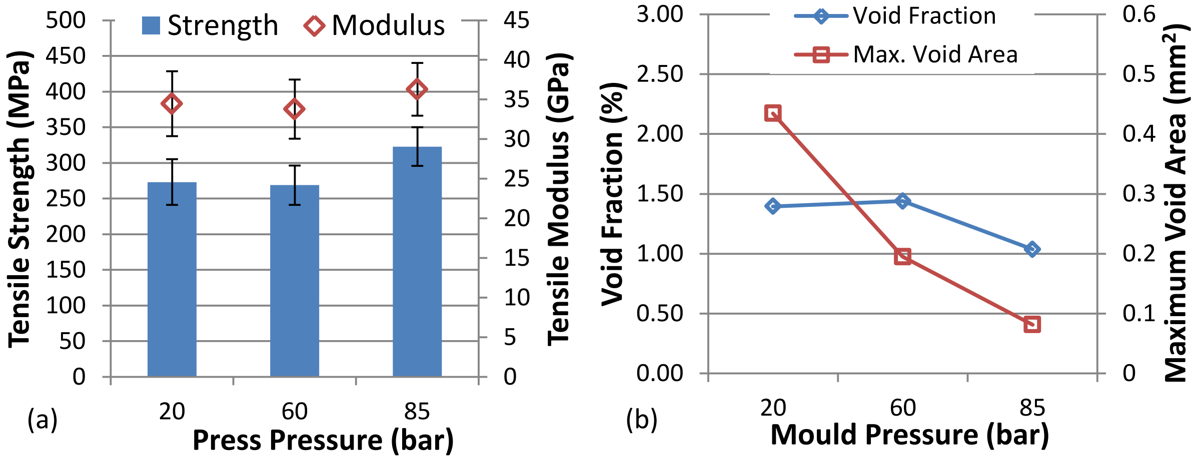


Figure 8: The effect of mould pressure on tensile properties (a) and void content (b) for 100% net-shaped compounds

A second study was conducted to understand the influence of moulding pressure for charge packs where flow was anticipated (i.e. less than 100% charge coverage). In addition, a range of fibre lengths was also investigated during this study to understand if the level of waviness for longer fibre lengths was affected by mould pressure. Tensile properties presented in ***Figure 9*** show that both the stiffness and strength are generally higher for 50% coverage plaques moulded at 20 bar, compared with similar plaques moulded at 85bar. This is more pronounced for the longer fibre lengths, as the degree of fibre waviness tends to increase with fibre length. The longitudinal strength increases by 33% for the 50mm fibre length and 40% for the 75mm fibre length. Furthermore, the tensile moduli were found to increase by 11% and 17% for 50mm and 75mm fibre lengths respectively.

According to ***Figure 10***, charge flow improves the likelihood of air removal. The void content is lower for the 50% charge coverage plaques than the 100% net-shape plaques, at all fibre lengths tested. In addition, ***Figure 10*** also indicates that the void content is lower for plaques moulded at 20bar when the charge size is 50%, compared with plaques moulded at 85bar with 100% coverage. This has the added benefit of reducing fibre waviness, as reported above.

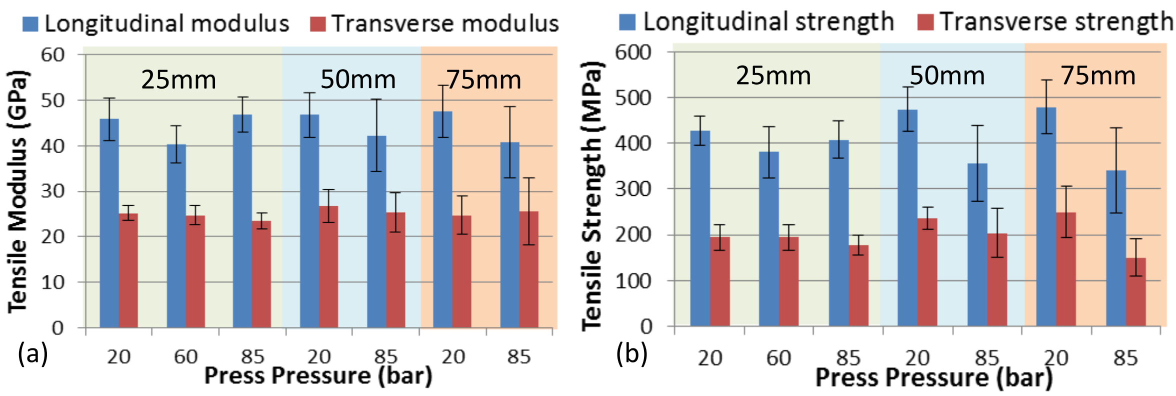


Figure 9: Tensile modulus (a) and strength (b) of different fibre length DFC compounds with 50% mould coverage and 50% Vf, varying the moulding pressure.

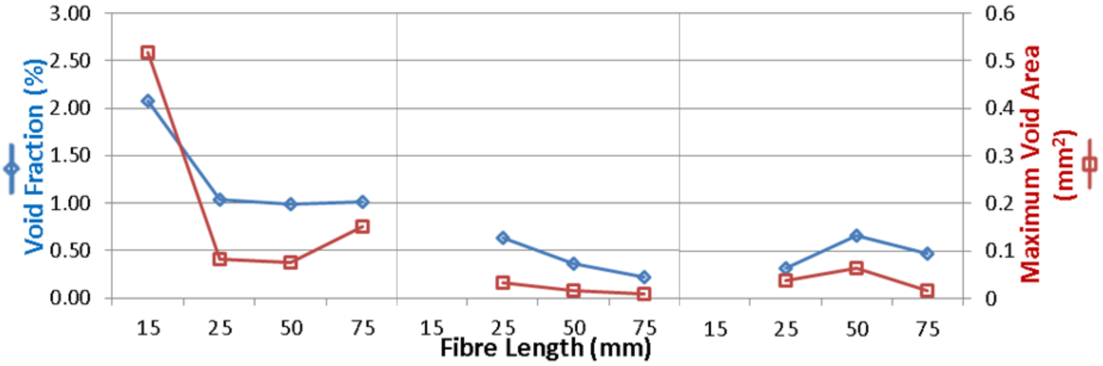


Figure 10: Void content for varying fibre lengths for 100% charge coverage at 85 bar (left), 50% charge coverage at 85 bar (middle), and 50% charge coverage at 20 bar (right)

4 CONCLUSION

A process is presented to manufacture tailored charges suitable for high-volume compression moulding. Directed Fibre Compounding (DFC) overcomes the challenges of producing carbon fibre/epoxy moulding compounds using conventional routes, to produce a material suitable for structural applications. Tensile stiffness and strength values of 36GPa and 320MPa are reported for isotropic materials, which can be increased to 48GPa and 480MPa with flow induced alignment. These values compare particularly well against commercial carbon fibre compounds, including those derived from expensive UD prepregs. The success of this process can be attributed to the high level of bundle impregnation achieved at the spray-deposition stage. This is a particular challenge when producing carbon fibre moulding compounds using glass SMC techniques, which is why most commercial epoxy versions are derived from UD prepreg.

Furthermore, it has been shown that there are two dominant mechanisms for minimising voids. Higher moulding pressures are required for net-shape (100% coverage) charges to collapse entrapped air, due to the lack of resin flow. Conversely, encouraging charge flow (smaller charge coverage) allows additional air to escape through the flash-gap, potentially enabling the moulding pressure to be reduced to achieve a high quality laminate. Lower moulding pressures also lead to reduced fibre waviness, particularly for longer fibre lengths, yielding higher tensile properties.

ACKNOWLEDGEMENTS

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