PRESSING-AND-FOLDING OF DISCONTINUOUS LONG FIBRE THERMOPLASTIC COMPOSITES AS AN ALTERNATIVE TO DIRECT COMPACTION

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Keywords: *Discontinuous Long Fibre Composites, Compression Moulding, Recycling.*

ABSTRACT

A novel pressing-and-folding moulding process is developed to determine the influence of flow on discontinuous long fibre thermoplastic composites based on ‘chips’ or ‘flakes’ cut from unidirectional (UD) tape, and to improve mechanical properties. Chips with dimensions of 25 mm x 25 mm were cut from glass fibre reinforced polypropylene UD tape with a fibre volume fraction of 45% and moulded into flat plaques using charges ranging from 50% to 12.5% tool coverage and compared to panels produced from near zero-flow direct compaction compression moulding. Material data was gathered for high-flow plaques produced from the novel pressing-and-folding process and compared to direct compaction. It was found that those produced using a high-flow pressing-and-folding method exhibited improved tensile properties. Scanning electron microscope (SEM) fractography shows increased fibre orientation in the test direction due to the high flow. Tensile properties were also shown to increase with the number of pressing-and-folding operations, leading to enhanced homogeneity of the DLF compound, and improved fibre dispersion, wetting and stress transfer. However, in contrast to alternative extrusion compounding operations all of this was achieved without significant fibre length reduction as a result of the mild mixing conditions during pressing-and-folding.

1. INTRODUCTION

Discontinuous long-fibre (DLF) thermoplastic composites are versatile composites that combine good mechanical properties with the versatility and processability of thermoplastic resins [1]. These materials are targeted to fill the metal replacement gap between semi-structural short-fibre reinforced thermoplastics (SRFP) and structural laminates based on continuous fibres [2]. DLF materials are typically produced by chopping high-fibre content UD tapes into ‘chips’ or ‘flakes. Due to their discontinuous nature, DLF materials can flow and produce complex geometries, making them ideal candidates for components such as brackets and fittings. Moreover, the inclusion of metallic inserts can enable further functional integration. In metal replacement, they reduce the need for complex assemblies and secondary assembly operations by moulding entire assemblies as a single component, while their use can also result in significant weight savings.

As with other discontinuous fibre composites, fibre - or in this case chip length - is a critical parameter governing the mechanical performance of these materials, which makes the preservation of fibre length while processing an important issue. Previous studies have shown that if fibre lengths are sufficiently high, values for elastic modulus and tensile strength can approach that of continuous fibre reinforced quasi-isotropic laminates [3, 4]. DLF thermoplastic composites are usually produced by slitting and cutting UD tapes or prepreg materials as in this way, chip length and, thus fibre length can easily be controlled. Moreover, these materials can be produced by repurposing UD tape manufacturing waste as tape edges are usually trimmed due to fibre distortions, providing an excellent feedstock material for DLF thermoplastic composite. Often these waste materials are shredded and used in injection moulding operations, leading to significant fibre length and property reductions. However, DLF chips are well suited for both direct compression moulding or flow moulding. Direct moulding is a near-net shape hot-compaction process of chips without excessive flow. Flow moulding involves an initial charge that partly covers the tool and can produce more complex geometries such as ribs and bosses. Several authors have shown that flow can improve the mechanical properties of DLF thermoplastic composites [5-7]. This is believed to be due improved homogeneity and a reduction of polymer-rich regions throughout the composite as well as improved wetting of fibres by the matrix due to chip breakdown caused by the shear forces during squeeze flow.

This paper aims to systematically study the influence of flow on the structure and properties of DLF thermoplastic composites from cut UD tapes. A folding and pressing technique, inspired by previous work to improve nanofillers' dispersion in polymer matrices [8], was used to vary tool coverage and flow of DLF chip charges, while repeating pressing-and-folding operations were used to study the influence of flow on homogeneity and mechanical properties of the compound. Mechanical properties of high-flow panels were compared to panels produced using direct compaction moulding to determine the influences of flow on these materials. Scanning electron microscopy (SEM) was used to investigate the morphology and failure mode for both high and low-flow DLF thermoplastic composites.

2. MATERIALS AND METHODS

2.1 MATERIALS

The base material used in this study was a glass fibre reinforced polypropylene (GF-PP) UD tape, which was cut into DLF thermoplastic composite chips with dimension 25 mm x 25 mm (Figure 1). The materials were supplied by Van Wees UD and Crossply Technology (Netherlands). The material contained 70 wt.% (45 vol.%) glass fibre, which was confirmed by thermogravimetric analysis (TGA).

Figure 1. DLF GF-PP chips used for moulding studies.

2.2 MANUFACTURING

Flat plaques were manufactured using closed cavity tooling with a shear edge to produce A4-sized composite panel. The tool was mounted on a 150 tons Langzauner composite press.

DIRECT COMPACTION OF DLF CHIPS

Baseline mechanical properties were determined by direct compaction processing of DLF thermoplastic composite chips into flat plaques using near 100% tool coverage charges. Chips were preheated to 200 °C and held for 3 min using a heated compaction table (Mikutherm-Optimal, Elkom). An aluminium frame measuring 300 mm x 200mm was used to achieve consistent charge dimensions (Figure 2), and 2 mm shims were placed onto the compaction table to limit squeeze flow during heating and to maintain charge dimensions. The charge was then transferred to the press and moulded at 200 bar. Figure 2 also shows a plaque produced by the direct processing of DLF thermoplastic composite chips. Tensile properties found for these baseline plaques are given in Table 1:

Table 1. Baseline mechanical properties of direct processed DLF composites.

Material Properties	DLF GF-PP Direct Processed
Density (kg/m^3)	1650
Young's modulus (GPa)	14.1
Tensile strength (MPa)	55
Fibre volume fraction (%)	45

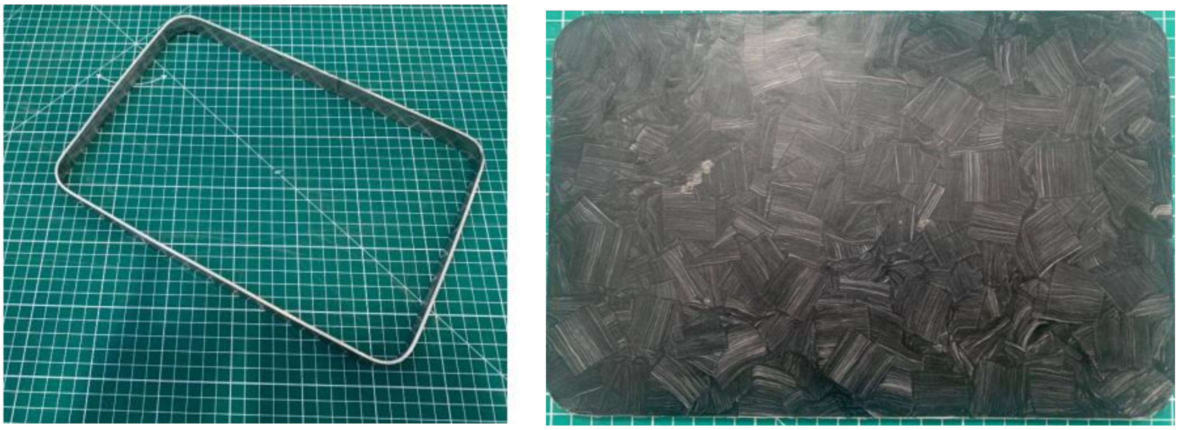

Figure 2. Aluminium frame used for charge preparation (left) and flat plaque produced via direct compaction processing of DLF GF-PP chips (right).

PRESSING-AND-FOLDING OF DLF CHIPS

Folding of molten DLF thermoplastic composite chip charges was used to create variable charge dimensions whilst increasing the amount of flow required for the material to fill the cavity when pressed. Increased flow is expected to improve the homogenization of the DLF material as it will facilitate breakdown of the chips. However, due to the mild mixing action in this process as compared to extrusion compounding this should be achieved without significant fibre length reduction, producing components with greater tensile properties than those produced through extrusion compounding processes.

Three different folding cases were trialed: (1) folding the charge into halves, (2) folding the charge into quarters, and (3) folding the charge into eighths. Figure 3 shows a schematic for each folding operation and how the molten DLF charges were folded to achieve this. Table 2 details the tool surface coverage of each charge and the amount of flow required to fill the cavity:

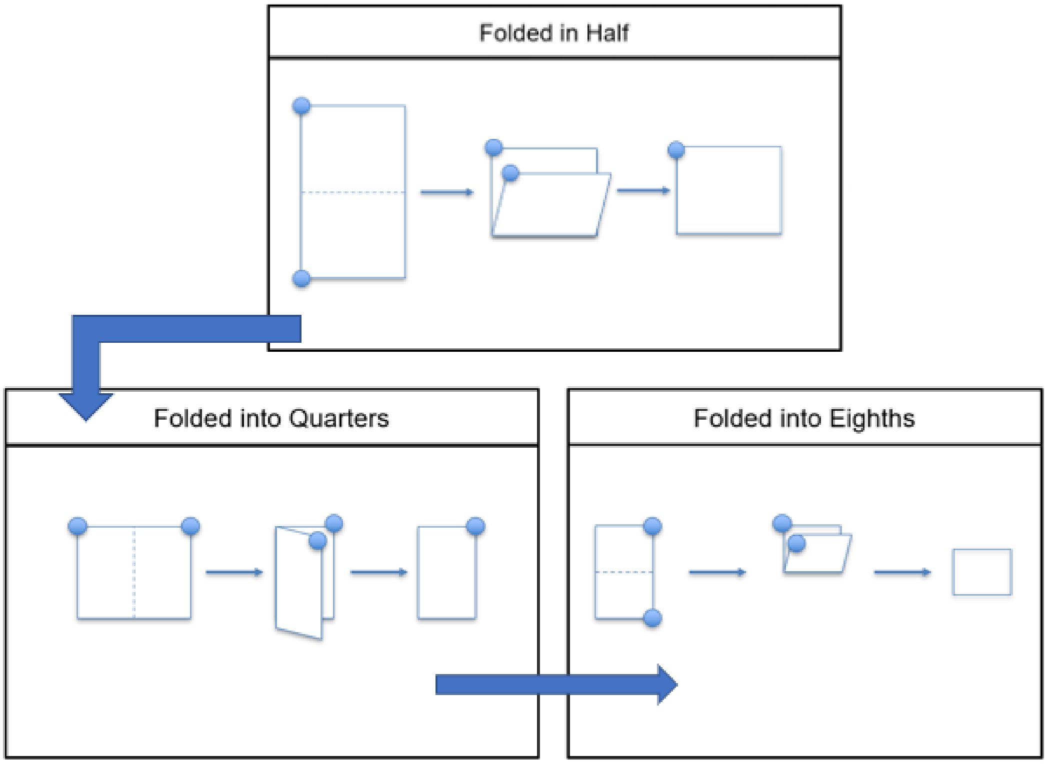

Figure 3. Schematic of the three folding cases.

Table 2. Tool surface coverage and required flow to fill the mould for each folding case.

Folding case	Tool coverage (%)	Flow to fill mould (%)
Folded in halves	50	50
Folded into quarters	25	75
Folded into eighths	12.5	87.5

Charges were heated using the same compaction table and heating cycle as for the direct compaction processed DLF thermoplastic composite chips. Once preheated to the processing temperature and held for 3 min, charges were folded into either halves, quarters, or eighths. These charges were then reheated back to processing temperature in the heated compaction table for a further minute before being transferred to the press for processing.

The above manufacturing process was repeated for each folding case to explore the effect of multiple pressing-and-folding operations. For repeated pressing-and-folding, an initial charge was preheated, folded, and then reheated to processing temperature before being transferred to the press. The produced plaque was then again reheated, folded, and reheated to processing temperature and presses to a plaque. For all folding cases, this process was repeated up to three times. Figure 4 shows an example of a plaque folded in half and pressed after two repeats.

Figure 4. Flat plaque produced from DLF GF-PP chips via pressing-and-folding method by folding in half and pressing with 2 repeats.

2.3 CHARACTERISATION

Tensile tests were conducted using a 30 kN static Instron test frame (Instron 3367) fitted with a 30 kN load cell. Tests were conducted per ASTM D3039 using straight-edged samples and using 25 mm wedge grips. The strain was measured using an Instron mechanical extensometer with an 80 mm gauge length.

Scanning electron microscopy (SEM) analysis was done using a desktop Hitachi TM3030+ system with integrated EDX analytical tools. Samples were sputter coated with Au/Pd, and images were taken of the fracture surface of tested specimens.

3. RESULTS AND DISCUSSIONS

3.1 MANUFACTURING

As seen in Figure 2, in case of direct compaction of DLF thermoplastic composite chips with near-zero flow, chips in the finished component show minimal distortion and breakdown and form a random platelet-like structure.

The importance of flow when processing these materials has been shown several times in recent literature. Leblanc et al. [5, 6] has shown that flowing DLF composite chips results in fibre alignment in the flow direction and chip thinning due to shear forces during flow. This leads to significantly improved tensile properties. However, when dealing with loose DLF composite chips, consistent charge size can be difficult to obtain, often resulting in variations in charge dimensions and, thus, increased or decreased flow in the mould cavity. This can lead to variations in the properties found in produced components, as the amount of flow required to fill the cavity varies with charge dimensions. Using a framing tool for initial chip placement and shims to prevent excessive squeeze flow resulted in consistent charge sizes when folded in halves, quarters, and eighths. In case of consistent flow lengths, the repeated pressing-and-folding process acts much like the well-known ‘baker’s transformation’ process of repeated stretching and folding as also introduced in polymer processing [9]. The surface finish of the pressed and folded plaques resembles more that of other flow moulded composites like sheet moulding compound (SMC).

3.2 MECHANICAL TESTING

Figure 5 show the average Young's modulus values for all folding cases and repeated pressing-and-folding operations. It shows that each additional fold leads to an increase in Young's modulus. This is expected because each fold reduces the charge size and increases the flow path required to fill the cavity, leading to fibre orientation. Furthermore, each time the moulding cycle is repeated for each pressing-and-folding case, the modulus slightly increases further. This is likely due to improved mixing as a result of shear flow. To investigate this further, micro computerized tomography (μ-CT) scans are planned to quantify fibre alignment and fibre dispersion as a function of the number of moulding cycles.

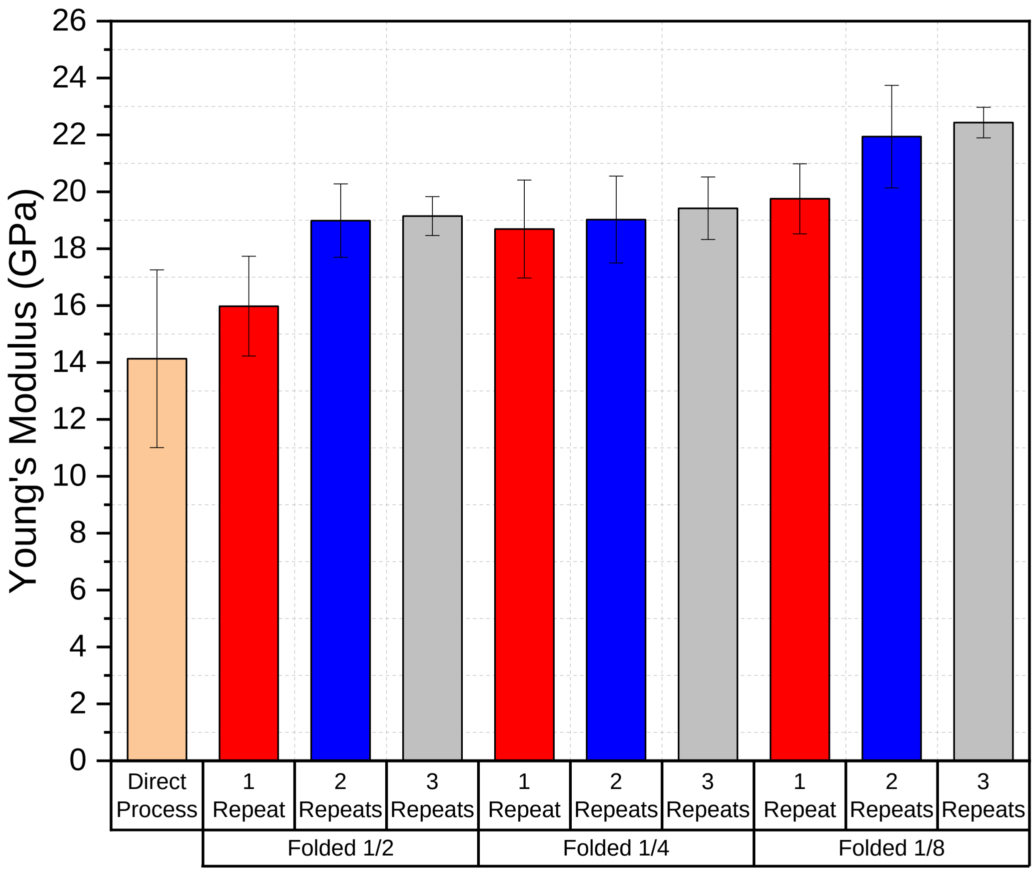

Figure 5. Youngs' modulus of DFL GF-PP for all moulding trials.

Figure 6 shows a similar trend for tensile strength. However, here the difference between one and two plus moulding cycles is more significant, especially for plaques produced by folding into quarters and eighths. This is due to increased homogeneity of the DLF compounds with repeated moulding, leading to improved fibre dispersion, wetting, and matrix interdiffusion [10]. As a result, interfacial properties and stress transfer are improved, leading to an increase in tensile strength with the number of moulding cycles. This explains why folding a charge into quarters or eighths leads to such a large increase in tensile properties as folding into quarters and eighths increases the number of DLF layers by a factor of 4 and 8, respectively. Thus, as the number of layers increases in this baker's transformation-like process, so does the homogeneity of the compound, resulting in improved mechanical properties.

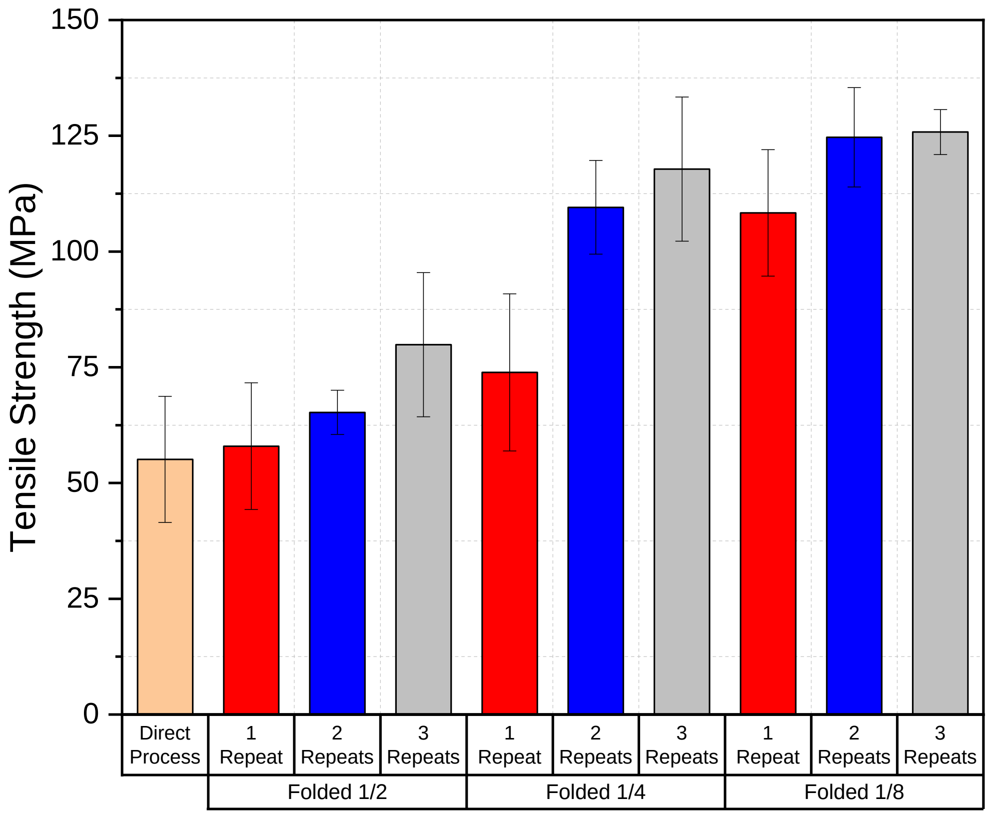

Figure 6. Tensile strength of DLF GF-PP for all moulding trials.

3.3 COMPOSITE MORPHOLOGY

Figures 7 shows SEM images of fracture surfaces of directly compacted DLF plates and composite plates that were folded into eighths and pressed with 2 repeats. Comparing Figure 7A and 7B clearly shows the effect of the pressing-and-folding method on improved fibre-matrix dispersion and wetting. In Figure 6B fibres are more evenly dispersed across the failure site when compared to Figure 6A. For both samples, fibres appear to be largely aligned with the test direction, but more quantitative analysis is required to determine actual fibre orientation.

(A) (B)

Figure 7. SEM image of DLF-based GF-PP laminates: (A) direct processed and (B) folded into eighths and pressed with 2 repeats (x30 magnification).

4. CONCLUSIONS

The presented pressing-and-folding produces DLF-based thermoplastic composite components with improved mechanical properties over those achieved by direct compaction processing. It has been shown that with repeated pressing-and-folding and a high utilisation of material flow, respectable mechanical properties can be achieved with glass fibre reinforced polypropylene composite chips.

Young's moduli up to 24 GPa and tensile strength values of up to 140 MPa were achieved with a simple pressing-and-folding method for DLF GF-PP compound. The repeated stretching and folding steps in this baker's transformation-like process improves compound homogenization, fibre dispersion, wetting and stress transfer. The repeated size reduction of the chips induced by the pressing-and-folding resulted also in a higher degree of fibre alignment, to be confirmed by µ-CT scanning.

ACKNOWLEDGEMENTS

This project is funded by the Warwick Industrial Fund (WIF) and Van Wees UD and Crossply Technology in the Netherlands. The authors would like to acknowledge Mr. Rien van den Aker and Van Wees UD and Crossply Technology for fruitful discussions and continued support throughout the project and for supplying the material for this study.

The µ-CT scanning data used in this article was acquired using the Free-at-Point-of-Access scheme at the National Facility for X-Ray Computed Tomography (NXCT) and carried out at the Centre for Imaging, Metrology, and Additive Technologies (CiMAT) at the University of Warwick. The authors would like to acknowledge Dr. Paul Wilson for sharing his expertise in this area and for producing µ-CT scanning data.

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