Pressing & Folding of Discontinuous Long Fibre Thermoplastic Composites as an Alternative to Direct Compaction

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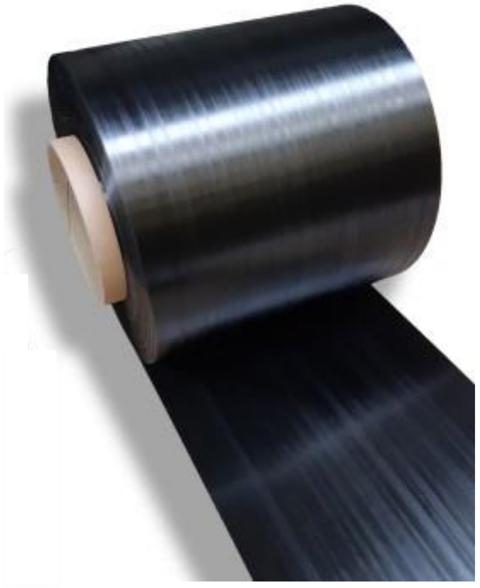
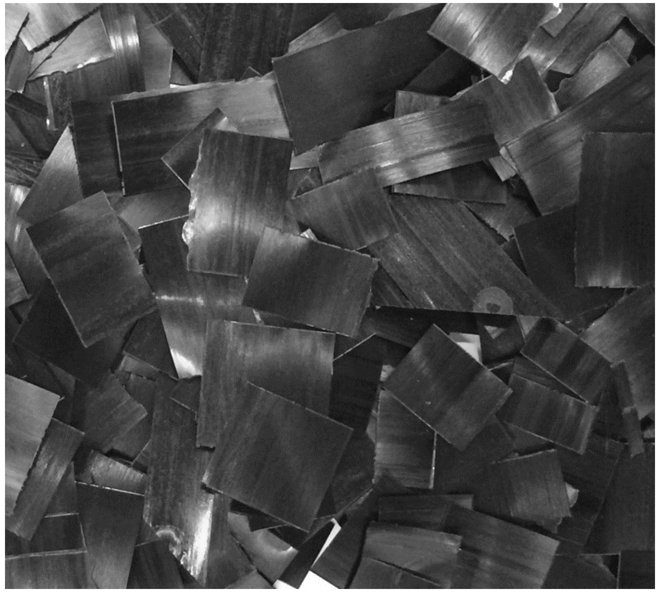
Discontinuous Long Fibre (DLF) Thermoplastic Composites

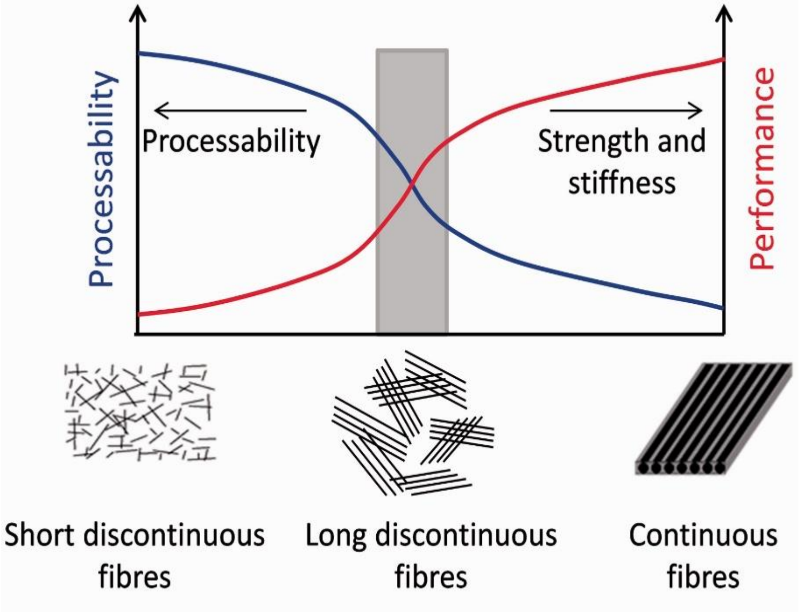
- DLF composites potentially offer a good **balance of mechanical properties and processability**, making them highly sought after for metal replacement in various industries, including automotive, aerospace, and consumer goods.
- DLF composites offer the opportunity to **repurpose manufacturing waste** such as cut-offs and edge trimmings of UD tapes.



UD thermoplastic composite tape



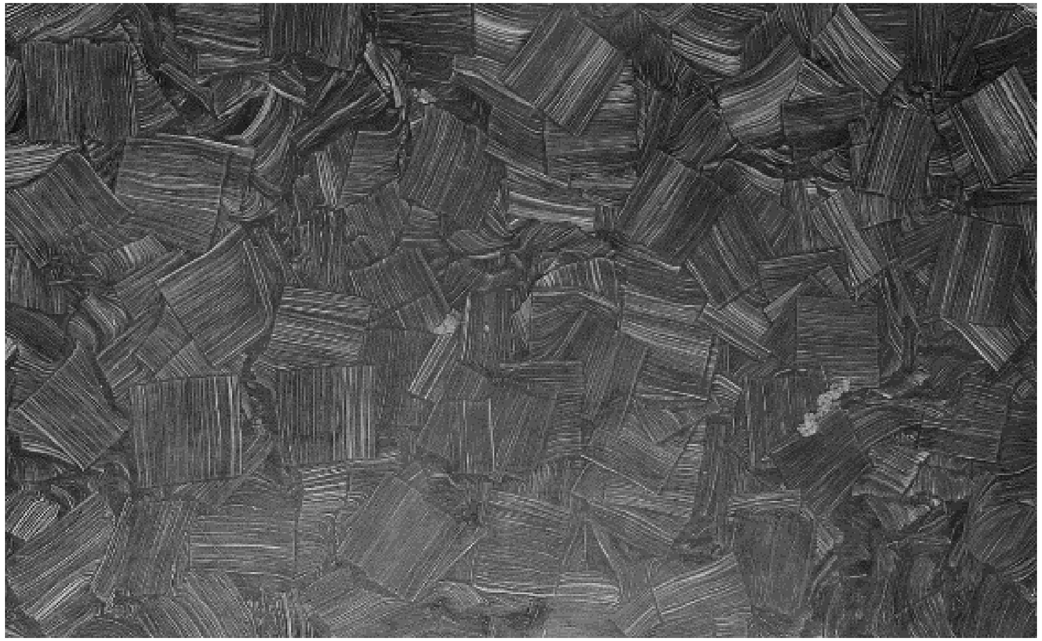
DLF thermoplastic composite "chips"



Mechanical properties and processability of DLFs
(Visweswariah et al, J. Reinf. Plast. Comp., 2018)

Direct Compaction of DLFs

- Direct compaction of PP-GF60 DLF thermoplastic composite tapes provides a simple **“near net-shape”** manufacturing process with minimal flow.
- DLF chips remain intact throughout the meso-structure after hot-pressing.



PP-GF60 DLF thermoplastic composite plate manufactured by direct compaction processing

Tensile Properties	Initial DLF data	Standard PP-LFT
Young’s Modulus [GPa]	14.1	8-10
Tensile Strength [MPa]	55	100-110

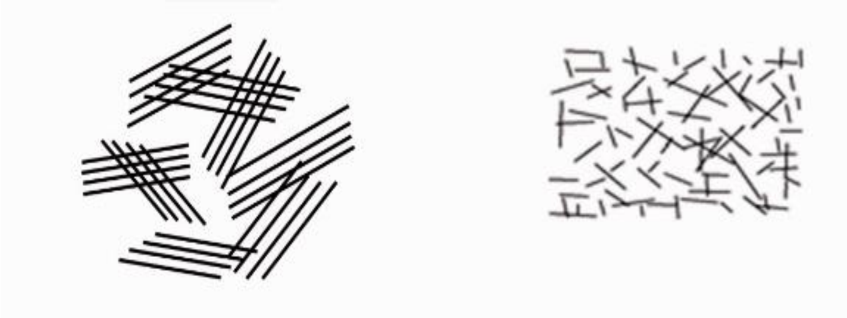
Data from initial mechanical characterisation of PP-GF60 DLF thermoplastic composite manufactured by direct compaction processing

Failure and Stress Transfer in DLFs

- Stress transfer in DLFs occurs at the meso-scale (tape-level) rather than the micro-scale (fibre-level).
- The relatively **low-stress transfer area** in DLFs can lead to failure at the tape-tape interface and poor tensile strength.
- DLFs can suffer from dry fibres due to poor wetting, leading to early failure.

Dry fibres at fracture initiation site

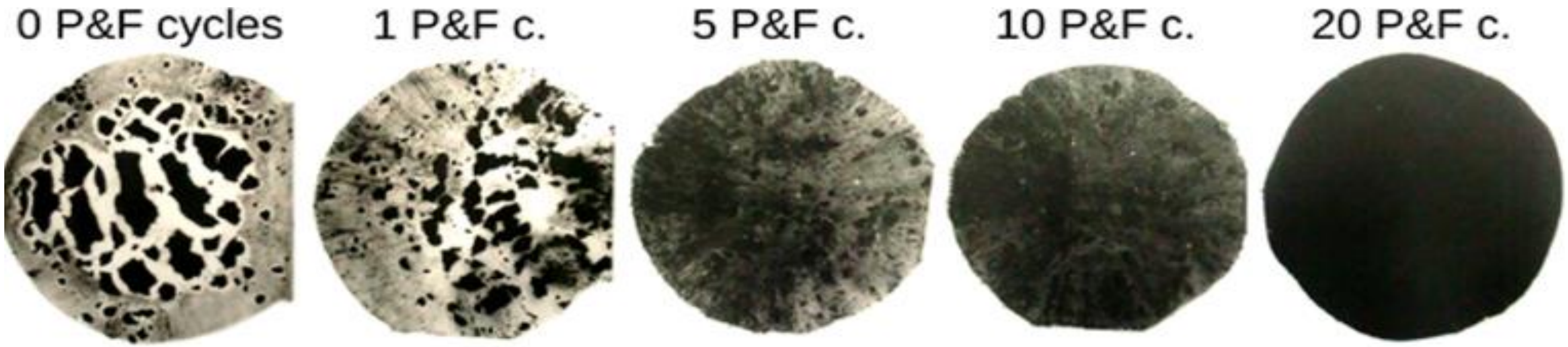
Failure along perimeter of the cut tape



*The total interfacial areas of two composites with a volume of 10 cm^3 based on either DLF cut tapes of 25x25x0.25 mm^3 or 50 vol% GF (Ø 14 µm) are resp, 4 m^2, and 140 m^2, i.e. a **35x lower interfacial area for stress transfer** than at fibre–matrix level !*

Baker's Transformation – Increasing the Interfacial Surface Area

- Baker's transformation involves stretching the dough and then folding it on itself and repeating the process. It is the process of filo pastry and croissant making.
- Baker's transformation has been used as a multilayering technique in polymer processing[1,2]
- Recently a **pressing & folding (P&F) multilayering technique** was shown to be effective in creating well-dispersed and homogenous graphene nanocomposites[3]

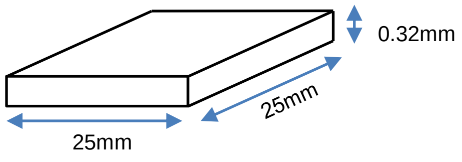


The effectiveness of successive pressing & folding of ultrahigh loadings of graphene nanofiller in a polymer matrix. (Santagiuliana et al. ACS Nano 2018).

1. Hiltner, Baer, et al., Polym. Eng. Sci., 1997
2. Gao, Peijs, et al., J. Appl. Polym. Sci., 2018
3. Santagiuliana, Peijs et al., ACS Nano, 2018

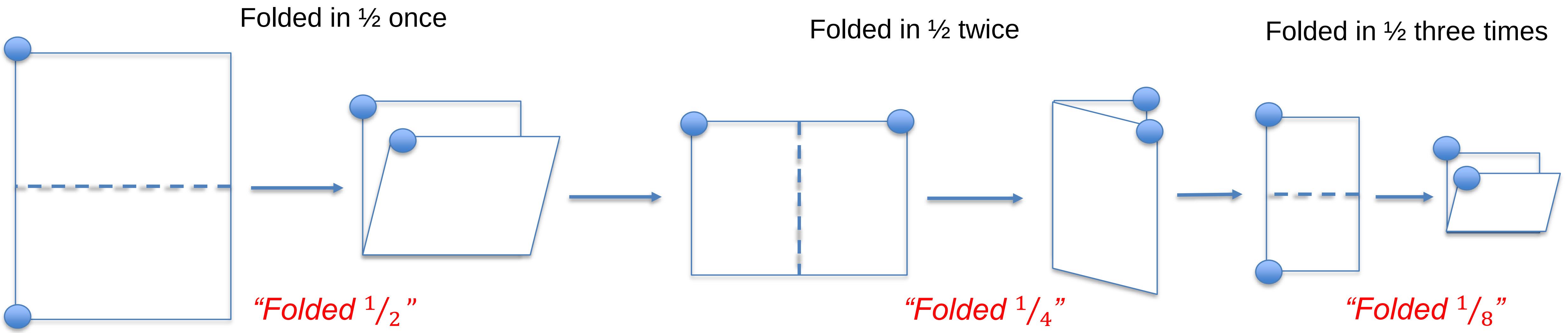
Pressing & Folding of PP-GF60 DLFs - Folding

- 2.5mm thick plates were manufactured, using 25mm x 25mm x 0.32mm cut tapes.
- Each DLF charge was preheated and folded in half up to three times and subsequently pressed into plates, each P&F doubles the number of layers.
- Objectives: (1) To **increase the interfacial area** between tapes and improve **stress transfer**, (2) to **improve fibre wetting and healing between DLF tapes** without excessive fibre breakage as in the case of extrusion compounding, (3) to **maintain a multilayered structure** with planar (2D) fibre orientations rather than fully random (3D) orientations.



PP-GF60 DLF chip dimensions

"2D planar random fibre orientations have higher reinforcing efficiencies (33%) than fully 3D random (20%)"



Pressing & Folding of PP-GF60 DLFs - Pressing

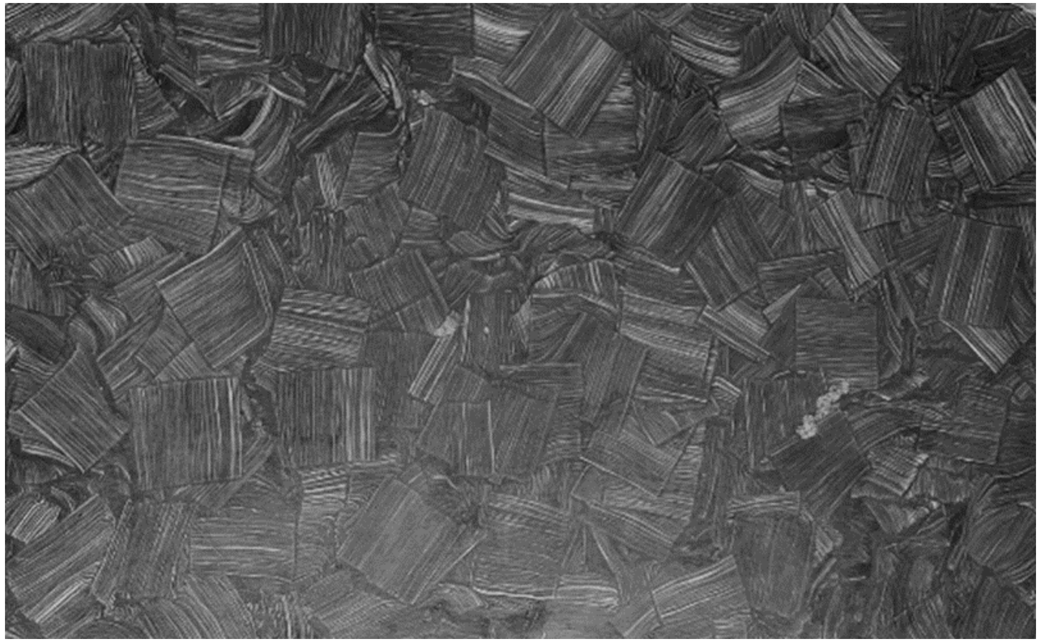
Charge preheated to 210°C → Charge folded → Charge pressed at 130 bar → DLF plate removed from tool

Process repeated up to 3 times for each folding case

One Repeat = One Moulding Cycle

Pressing & Folding of PP-GF60 DLFs - Morphology

- DLF tape breakdown throughout the meso-structure for plates produced by the P&F method. Tape thinning by (transverse) flow without fibre breakage.
- Surface finish resembles more that of traditional flow materials (i.e., SMC).



PP-GF60 DLF plate manufactured by direct compaction processing

GF-PP60 DLF plate manufactured by P&F. Folding into eighths and pressing with 3 repeats

Pressing & Folding of PP-GF60 DLFs – Mechanical Properties

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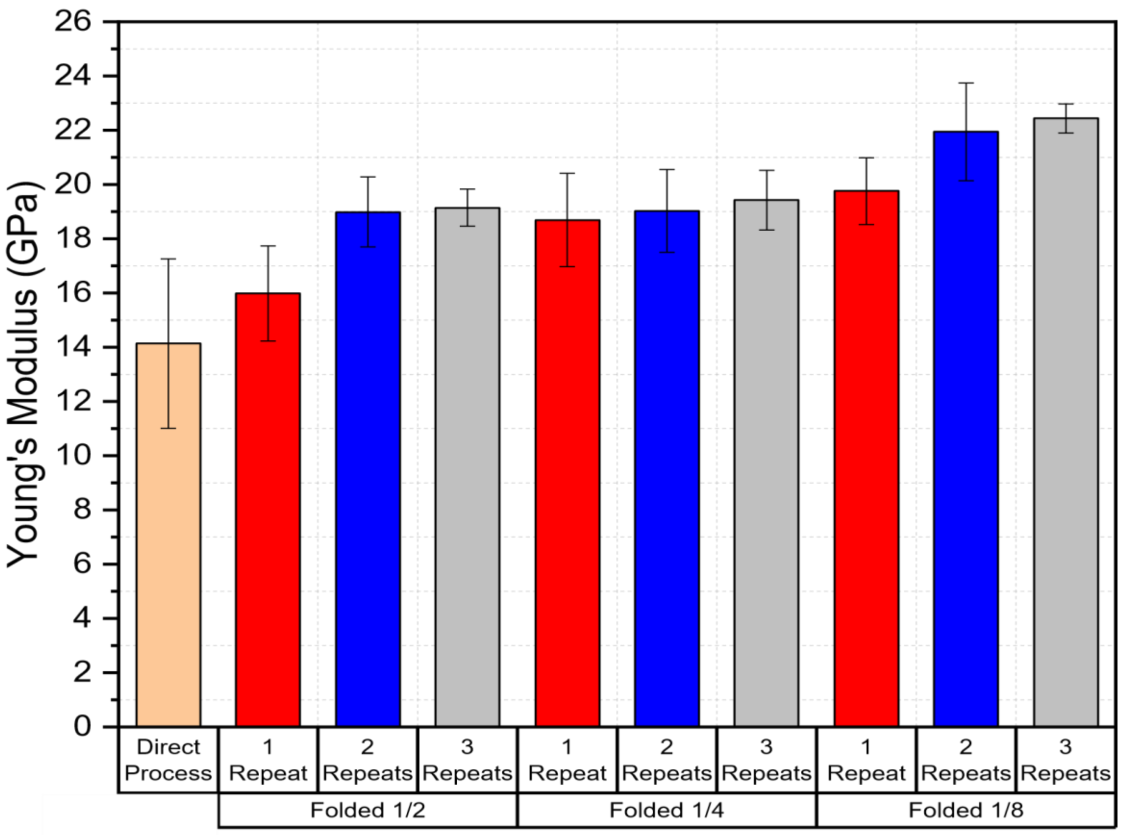
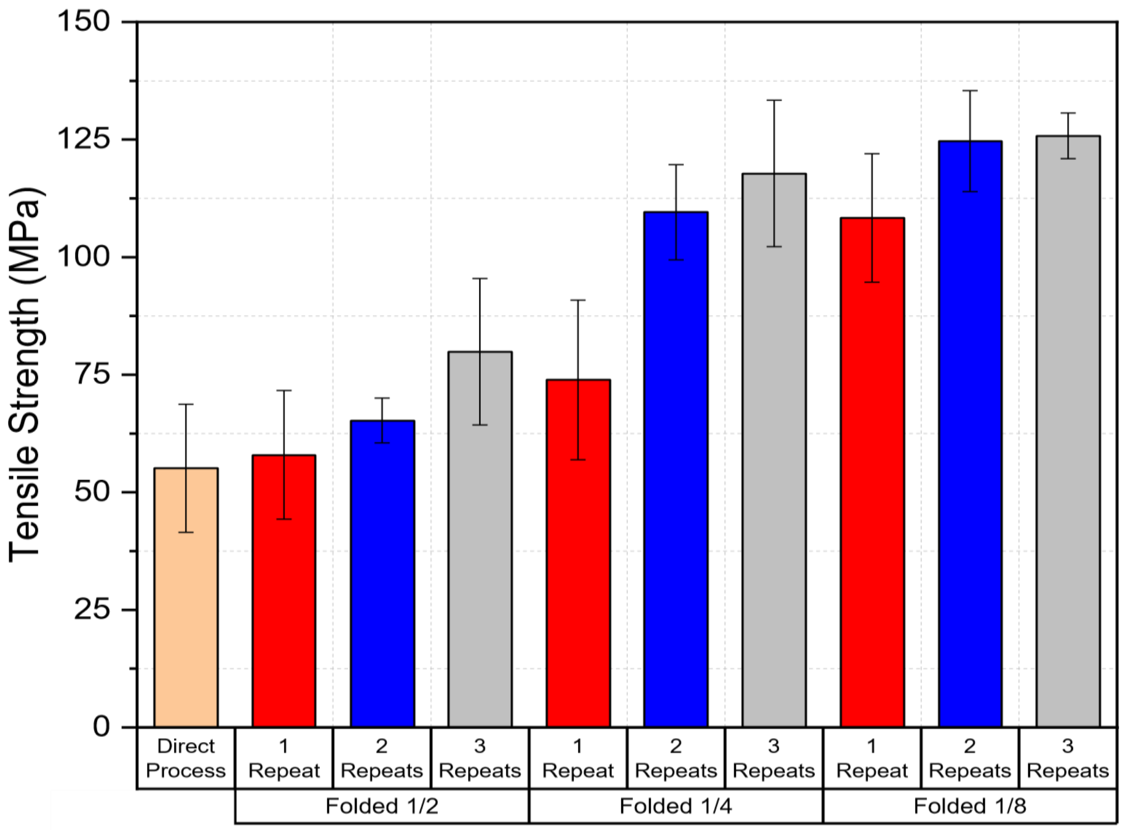




Comparison of tensile properties of plates manufactured via direct compaction and plates manufactured using P&F. For comparison, typical PP-LFT properties are 8-10 GPa and 100-110 MPa, respectively)

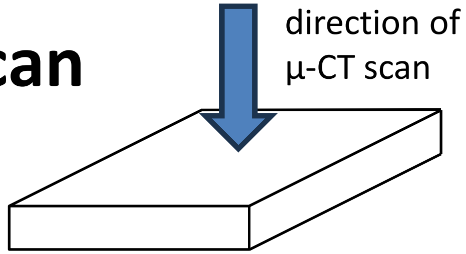
Pressing & Folding of PP-GF60 DLFs – Fractography

- Change in morphology was also observed in SEM.
- P&F samples showed **improved fibre-matrix dispersion and wetting**.
- **Change in failure mode** observed from tape pull-out for direct compacted samples to fibre breakage and pull-out for P&F samples.

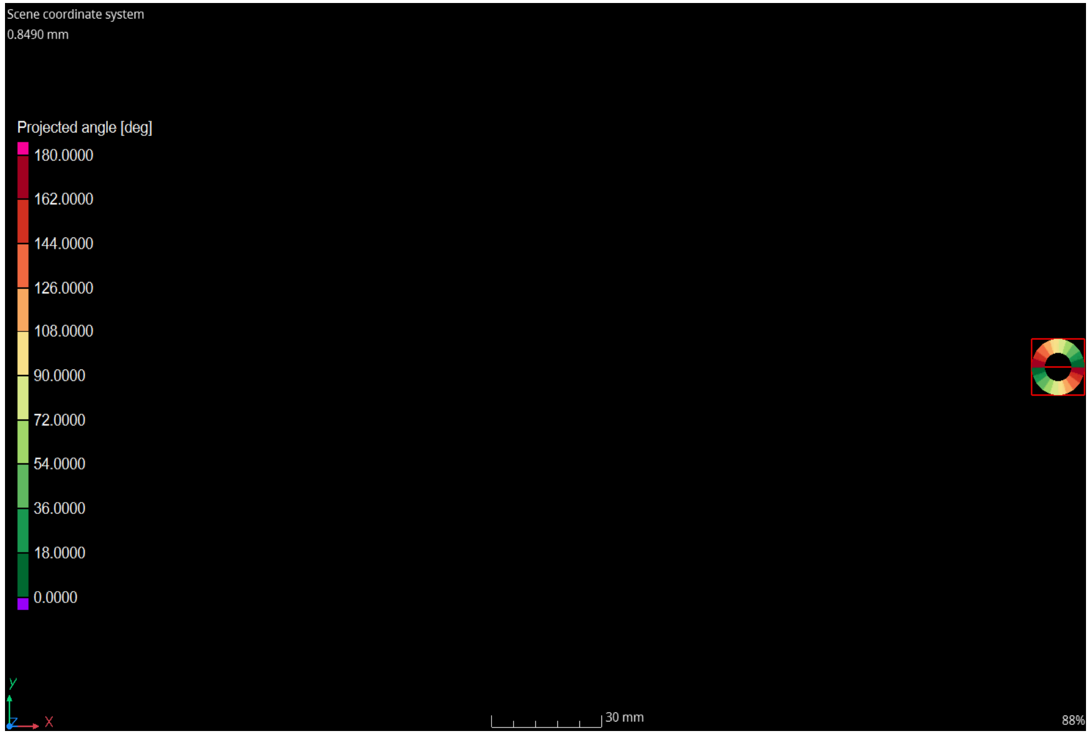
Direct Compaction

Folded into eighths and pressed with 2 repeats

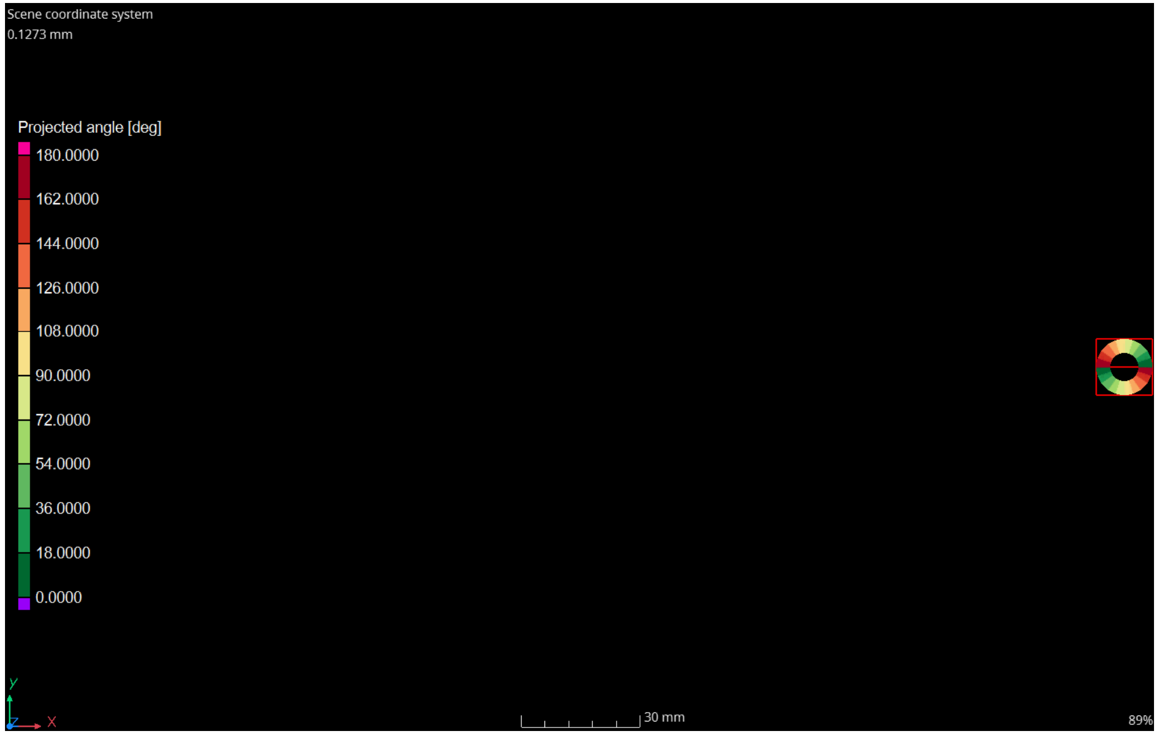
Pressing & Folding of PP-GF60 DLFs – Micro-CT scan



- In-plane (XY) scan shows DLF tape breakdown and apparent homogeneity after P&F



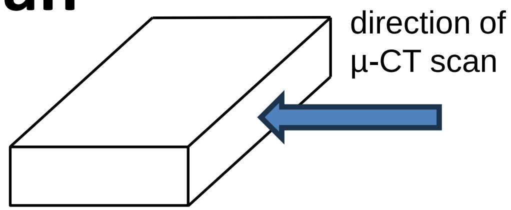
Direct Compaction

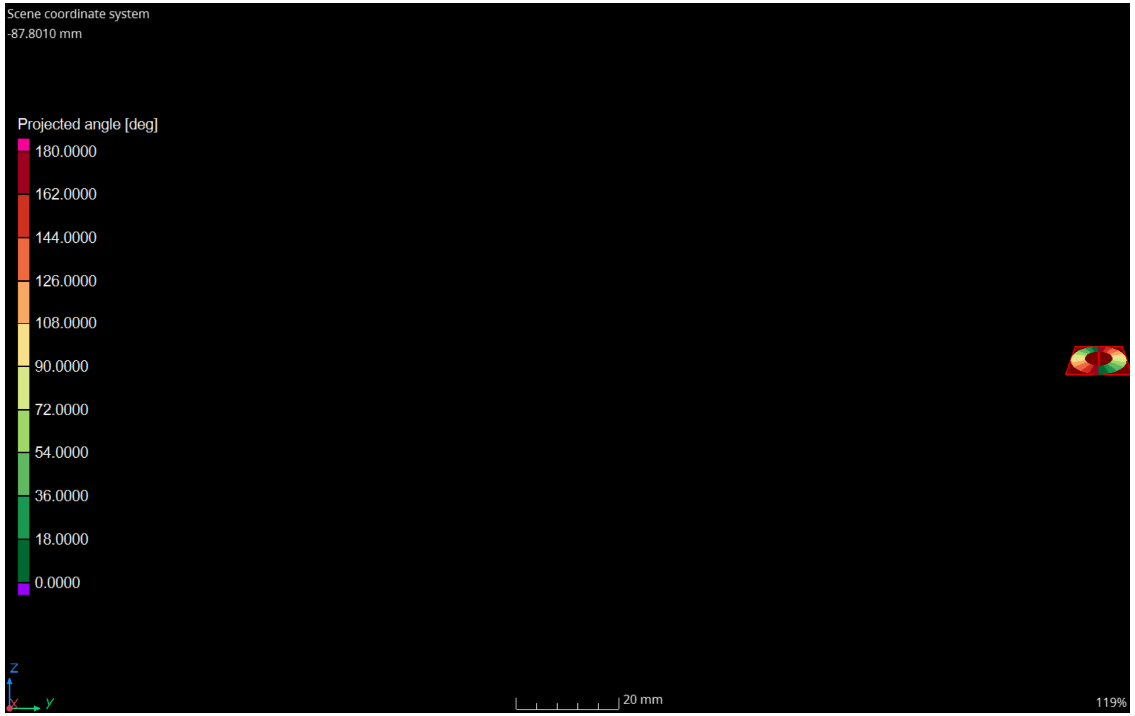


Folded into eighths and pressed with 2 repeats

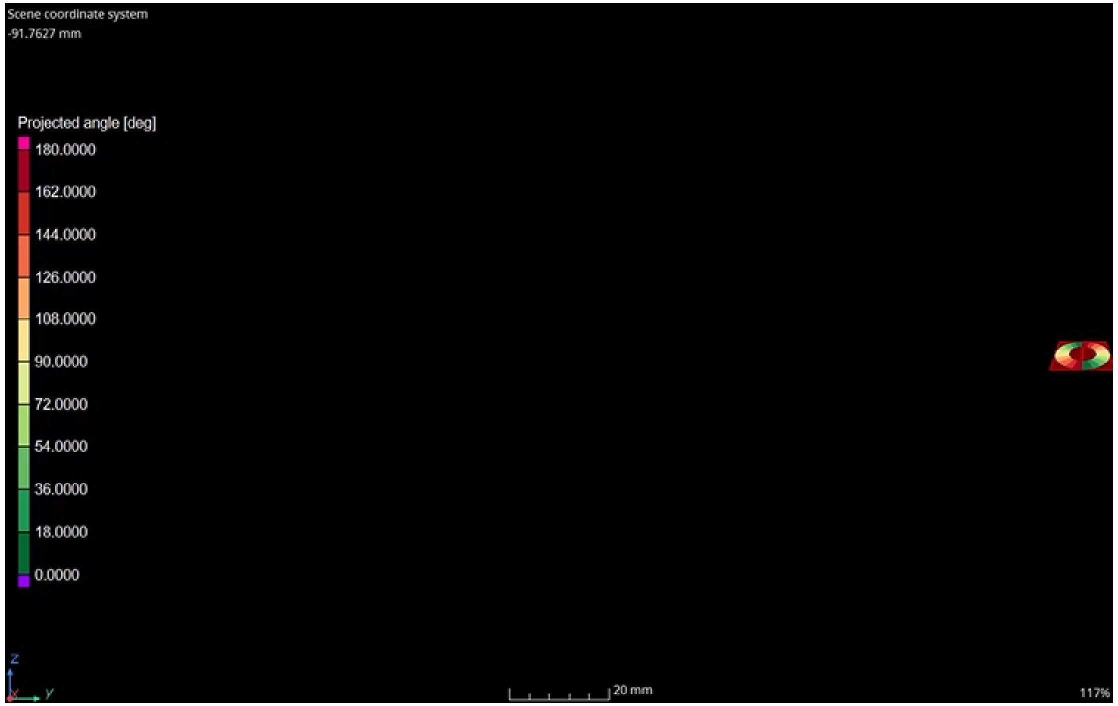
Pressing & Folding of PP-GF60 DLFs – Micro-CT scan

- Out of plane (XZ) scan shows multilayer structure after P&F





Direct Compaction

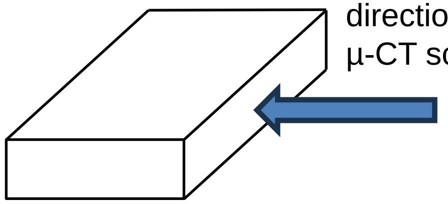


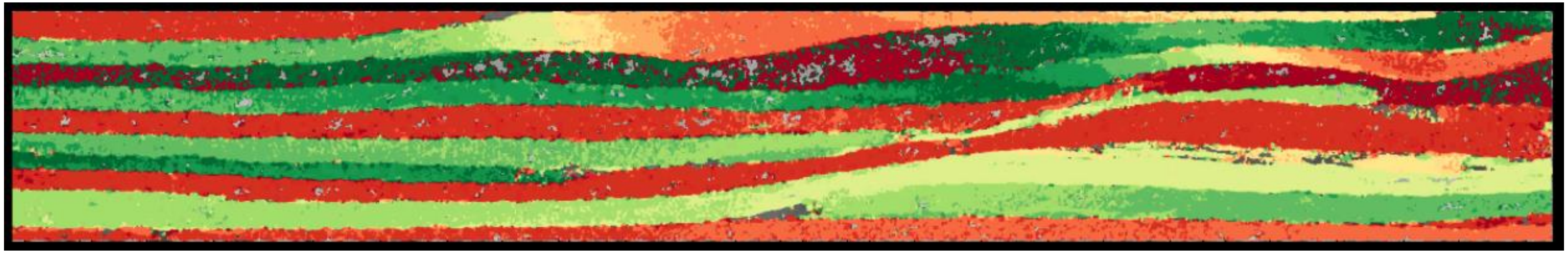
Folded into eighths and pressed with 2 repeats

Pressing & Folding of PP-GF60 DLFs – Multilayering

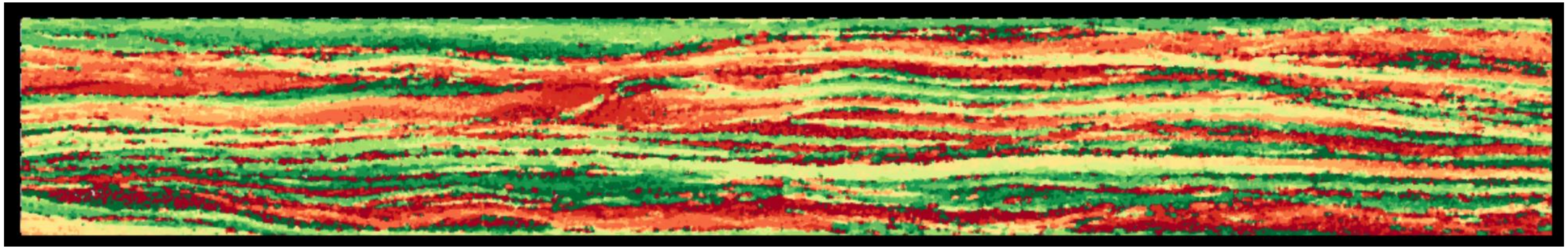
- Layered laminate structure remains mostly intact after P&F, indicating that fibre orientation will be closer to 2D (in-plane) random rather than 3D random.
- Number of layers increases for the same cross-sectional area after P&F.

ROM: $P_c = \eta_\theta P_f V_f + P_m V_m$ with θ = 1/3 for 2D random and 1/5 for 3D random





Direct compaction
10 layers



Folded into eighths and pressed with 2 repeats
33 layers

Conclusions & Future Work

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- The presented P&F method produced DLF-based thermoplastic composites with improved fibre wetting, improved healing between DLF tapes leading to enhanced stress transfer and mechanical properties over those achieved by direct compaction processing – using existing press equipment.
- The P&F method was able to improve mechanical properties by improving the meso-structure of the thermoplastic composites by a reduction in DLF tape thickness and **increasing the interfacial surface area and stress transfer**.
- This was achieved while largely maintaining a **multilayer laminated structure**, and without excessive fibre breakage as in the case of extrusion compounding.
- DLF-based thermoplastic composites showed a very high modulus (22 GPa) and respectable tensile strength (125 MPa) after P&F for PP-GF composites (typical PP-LFT properties are 8-10 GPa and 100-110 MPa, respectively)
- Future work will involve a more quantitative analysis and modelling of the multi-layering effect on stress transfer and a more quantitative analysis of µ-CT data to determine the effect of flow during P&F on fibre orientation.

Thank you for listening.

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