**Feasibility Study Final Report**

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**Feasibility Study (FS) Title**: Rewinding Tape Laying: can Direct End-of-Life Recovery of Continuous Tapes be a Step-change in the Sustainability of Thermoplastic Composites? (REWIND)

**PI name**: Dr Davide De Focatiis (2 hrs/week); co-Is: Dr Samanta Piano (1 hr /week), Dr Michael Johnson (1 hr/week)

**Research staff/students (*include names and % of time*)**:
RA: Dr Andrew Parsons (researcher Co-I, 80% FTE)

**Partners (include support from Industry)**: Boeing, Comfil

**Start date**: 01/01/2022

**End date**: 30/06/2022

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**Executive Summary**

This project explored the feasibility of recovering continuous thermoplastic prepreg from simulated end-of-life parts by a controlled thermal peeling process in such a way as to make the peeled plies re-useable in new parts with minimal post-processing. The fundamental challenges in this project lay in achieving effective separation of laminates with minimal disruption/damage of the fibres.

Despite thermoplastic composites being touted as recyclable materials, the actual means of doing so remains relatively poorly realised. The most recent comprehensive review on continuous fibre thermoplastic composites recycling identified only shredding, pyrolysis, and solvent removal as existing recycling methods. With high value continuous fibre thermoplastics all these methods result in either a downgrading of fibres, a waste of matrix material, or environmental issues and limitations with solvent solubility.

The feasibility study was able to successfully demonstrate that peeling of thermoplastic composites can be achieved with minimal force at temperatures close to the melting point of the matrix. It was also discovered that some composite materials also lend themselves to cold peel. The peeled tapes had higher surface roughness than the virgin materials, but the recovered materials were successfully remoulded into new components. The stiffness of the components made with peeled tapes is almost identical to that of components made with virgin tapes, and the strength is still under investigation.

The opportunity for impact is considerable, but there remains research to be done with respect to peeling a more realistic component and doing so in a more automated fashion. Digital twinning and automation will also need to be considered in a future study in this area.

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### Background

Although >100,000 tonnes of composites are produced in the UK each year, less than 15% is recycled, often through disruptive and energy intensive processes. Thermoplastic composites are by their very nature thermoplastic and offer the same unique opportunities for debonding and direct recovery without downgrading as they do in plastics manufacturing. Considerable understanding exists in the bonding mechanisms of thermoplastic prepregs, particularly since the peel test is widely used in characterising part quality. The aim of this project is to explore the feasibility of demanufacturing a thermoplastic composite through a controlled peel process. The objectives include: (1) the instrumentation of the peel process in order to establish optimal conditions for peel; (2) the identification of suitable metrological techniques for evaluating peel quality; (3) the evaluation of the mechanical performance of components remanufactured from peeled plies.

The fundamental challenges in this project lay in effective separation of laminates with minimal disruption/damage of the fibres. Interlaminar slip happens readily in thermoforming at melt temperatures and so peel with or without the insertion of a separating tool appears eminently achievable. Process degradation of the matrix may be a matrix-specific challenge which will require refinement of the thermal control. When dealing with high performance resins such as PEEK, PAEK and PEI, resin recovery by a peeling route could be enormously valuable, environmentally sustainable, and appears as yet entirely unexplored.

There are undoubtedly areas of industrial interest as the societal drivers for sustainability and the circular economy continue to apply pressure to the composites industries to become greener.

### Results/Deliverables/Outcomes

*[O1] Instrument a simplified peel tester with controlled heating for tape separation*

Lack of adhesion to metallic substrate meant that a conventional peel rig was not suited. A simple 2 ply peel set-up was devised, both at a small scale under isothermal conditions for instrumented study, and at a larger scale with localised heating for material recovery. Static loads were found to be suitable at both scales. The larger scale peel was supported by thermocouple and IR camera temperature measurements.

*[O2] Establish the conditions (eg. temperature, force, speed) required to successfully peel a layer of continuous thermoplastic tape from a simple consolidated structure*

Requirements for combinations of temperature and force of matrix detachment were explored at small scale using a rheometer with a highly controlled environmental chamber in three modes: transverse extension, lap shear, and small scale peel. Larger consolidated plies were successfully separated to produce two layers. Peel forces were generally low and peel rate was effectively limited by the rate at which heat could be transferred to the tapes. In some thermoplastics (PP/glass and PBT/glass) the separation could be achieved at room temperature with only marginally larger forces.

*[O3] Determine the most appropriate metrological technique to assess the viability of recovered material (in terms of waviness, matrix distribution, defects)*

An Alicona system utilising variable focus was successful in acquiring gross morphology and provided sufficient resolution to observe fibre alignment, waviness and defects. The system was used to study surface roughness of small scale and large scale peel samples. After peeling with no post-processing the peeled tapes had a higher surface roughness than the virgin tapes by around 1 order of magnitude, but were sufficiently flat to enable hand lay-up for post-processing. Some fibre disruption could be observed in the peeled tapes using a backlight.

*[O4] Attempt basic re-processing of peeled pre-pregs and determine composite properties*

Peeled tapes were successfully repressed into composites, and no obvious flaws could be seen by eye. The composite parts were cut into test specimens for subsequent stiffness and strength testing. The stiffness measurements of composites made from peeled tapes are comparable to those from virgin materials, and the strength measurements are still in progress.

*[O5] Provide a framework and initial data for a core project addressing the automated circular manufacturing of thermoplastic composites*

The project has produced considerable experimental data and observations, and these are in the process of being written up in two journal articles. The data is also being presented at two conferences.

A Synergy project was submitted to the Hub together with Bristol, Cranfield and the NCC, focused on thermoset recovery of single tow composite parts, but was unsuccessful. Further funding opportunities will be sought once the journal articles are accepted.

## Future Direction/Impact

The opportunity for impact is considerable, and there remains research to be done with respect to demanufacturing of more realistic components, as well as the automation required to achieve this at scale. There is much promise in being to exploit digital shadows of components in order to plan and execute the demanufacturing.

A 2020 patent from Germany has been identified that overlaps some of the concepts concerning peel of thermoplastic plies, but no publications have arisen relating to this. In order to circumvent this, future work may also focus on thermosets and vitrimers which are out of scope of the patent.

The scope of demanufacturing composite components is broad and the current state of research (TRL2, MRL1) lends itself well to a core project in a future hub, or to a larger EPSRC funded project invoving multiple partners with expertise ranging from composites manufacturing through to digital twinning, automation, materials technologies and life cycle analysis.

## Synergy with other Hub projects

The feasibility study aligns with The Future Composites Manufacturing Research Hub (CIMComp) sustainability challenges and Grand Challenges for Fibre Reinforced Composites (FRC). It fits under Hub research priority area (RPA) 5 (Recycling and re-use) and has longer term goals within RPA 1 (Rapid processing technologies) and RPA 4 (Inspection and in-process evaluation). It is aligned with workstream (WS) 8 (Thermoplastic Processing Technologies) and is potentially complementary to WS1 (Automated Fibre Deposition Technologies) and WS4 (Online Consolidation).

There is synergy with WS1 projects through developing fibre placement equipment for thermoplastic materials, to develop a multi-layer demonstrator component with digital shadow information.

| | | **Target / project** | **Actual achievements** |
|---|---|---|---|
| | **Project duration (yrs)** | 0.5 | 0.5 |
| | **Project Value (80% FEC)** | £ 50,000 | £49,356 |
| Project Metrics | **PhD students** | 0 | 0 |
| | **PDRAs (FTE per year)** | 1 | 1 (80%FTE) |
| | **Person years** | 0.5 | 0.5 at 80% |
| | **Project based partners** | 1 | 2 |
| | **Institutional support** | £ - | £ - |
| | **Industry support (Letters of Support)** | £ 12,500 | 12,500 |
| | **Additional leveraged grant income** | £ 125,000 | £ - |
| | **Additional industry leveraged income** | £ 60,000 | |
| | **Journal publications** | 0.5 | 2 |
| | **Conference papers** | 1 | 2 |
| | **Patent applications** | 0 | 0 |
| | **New collaborative research activity** | 0 | 1 |

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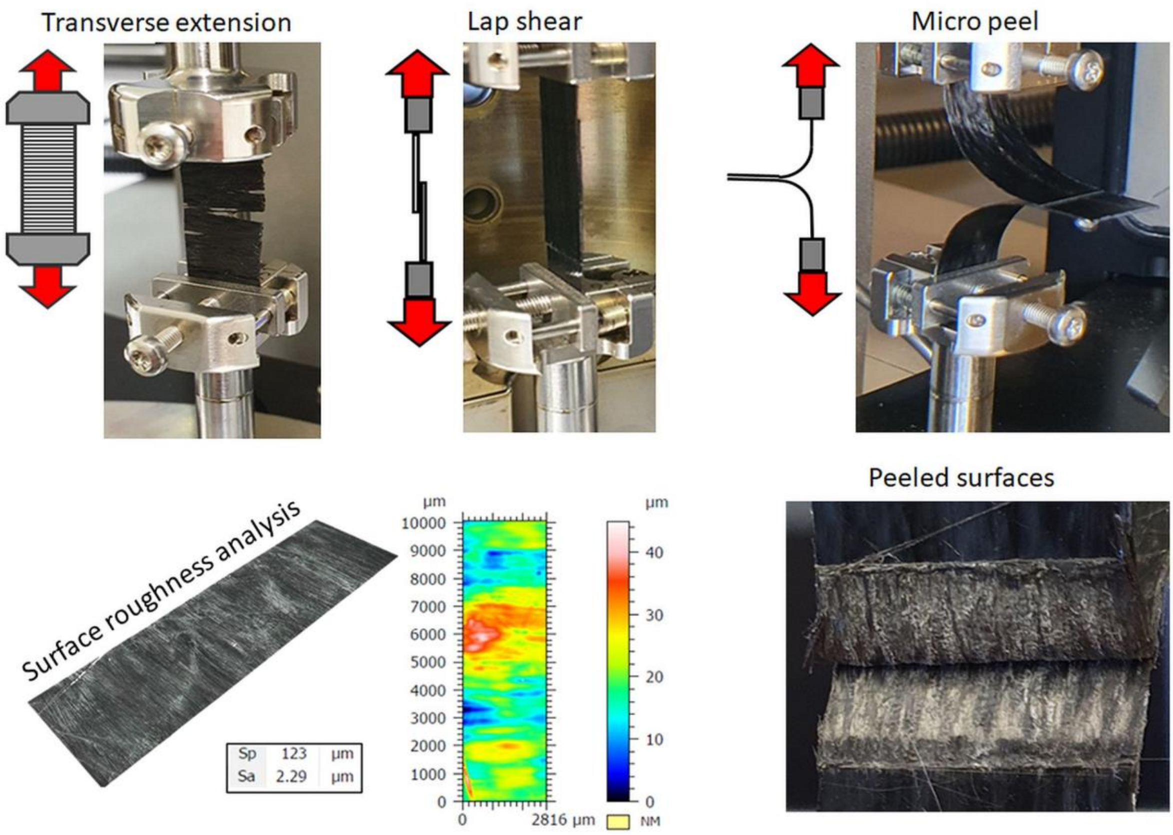
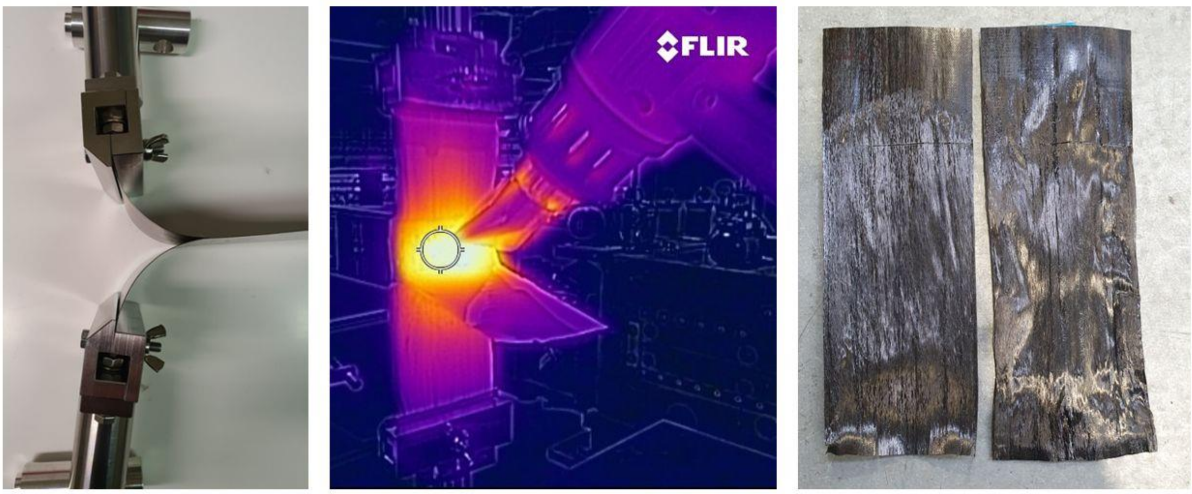



Methods employed to study the detachment of the matrix in order to peel consolidated composite plies. The surface roughness of the peeled surfaces was also recorded.




Large scale peeling of consolidated composite plies was achieved using heat and a small load. The peeled plies showed some surface disturbance but could be reprocessed into components with comparable properties to virgin plies.