Feasibility Study Final Report

Feasibility Study (FS) Title: Incremental Sheet Forming of Fibre Reinforced Thermoplastic Composites

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Partners (include support from Industry): NA

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Executive Summary

This feasibility project, Incremental Sheet Forming of Fibre Reinforced Thermoplastic Composites, aimed to form fibre reinforced thermoplastic (FRTP) sheet material using the diaphragm forming (DF) process enhanced by the robotic, incremental sheet forming (ISF) process. This method is termed the Hybrid Vacuum Robotic, or HyVR, forming process.

The traditional DF process allows shaping of pliable sheet material over a mould at forces limited by vacuum pressure. Pliability of FRTP occurs above the melt temperature. The low vacuum forming forces enables low cost, rapid prototyped moulds to be used. Scaling to large part sizes is possible with no penalty as the forming forces remain limited to vacuum levels. Two main defects arise using DF: 'bridging' and 'wrinkling'. FRTP bridging occurs at tight internal radii. Wrinkling of the reinforcement can develop when forming complex geometry. Strategically applying a supplemental normal force and a tangential smoothing force using a shaped end effector can overcome bridging and wrinkling defects, respectively. In the HyVR process, the path of the end effector is controlled by a computer numerical control (CNC) 6 axis robot. The over-arching aim is to manufacture large FRTP components in medium volumes (approximately 4-6 pph) and at low cost using the HyVR process.

In the feasibility study a lab scale HyVR cell was implemented. The forming strategy which drives the HyVR process through sequencing of the DF and ISF techniques was developed. In addition, experimental methods were defined to quantify the FRTP material characteristics (cone study) and associated thermal forming window. These are direct inputs to the HyVR forming strategy. Cone forming FRTP was not possible due to edge clamping of the inextensible reinforcement. Techniques to extend the forming window time still are required. Using the HyVR process, forming strategies were determined to produce single curvature parts without bridging. The quality of these components was equivalent to benchmark components made by hand layup. Forming strategies for double curvature components requiring in-plane fabric shearing were produced. While successful, further improvements to the forming strategy are required to minimise wrinkling in double curvature components.

This feasibility study aligns with the overall aim of the EPRSRC Future Composites Manufacturing Research Hub (the Hub) to promote the benefits of thermoplastic composites. Organisationally, the feasibility study forms part of Workstream (WS8): Thermoplastic Processing Technologies, within the research priority area: 'High-Rate

Deposition and Rapid Processing Technologies'. This seeks to meet the Grand Challenges of the Hub to enhance process robustness and develop high-rate processing technologies.

This feasibility study posed the research question, *"Can the HyVR process form FRTP sheet material to single and double curvature?"* The research conducted as part of this feasibility study demonstrated that this could be achieved.

Background

The ***aim*** of the feasibility study was to form fibre reinforced thermoplastic sheet material using the diaphragm forming (DF) process enhanced by the robotic, incremental sheet forming (ISF) process. This technique is termed the Hybrid Vacuum Robotic, HyVR, forming process.

Objectives of the feasibility study are to:

1. Characterise the forming limits of FRTP sheet material (continuous and discontinuous) via a "cone forming study".
2. Develop an optimal processing window for ISF of continuous FRTP composites of varying textile architectures.
3. Optimise the ISF of continuous FRTP composite sheets using a 6-axis robot to include clamping methods, heating systems, end effector path and continuous/punch forming action as well as end effector material and shape.
4. Demonstrate the technique of ISF over single and double curvature moulds (using a 6-axis robotic arm) to form a continuous FRTP composite part.

Industrial interest in the HyVR process has been evidenced in the form of letters of support from the following organisations to accompany the EPSRC Adventurous Manufacturing Round 2 Call (August 2020): Lotus Cars Limited, GKN Limited and the UKRRIN Centre of Excellence in Rolling Stock.

In addition, industrial interest in this research has been expressed by Aston Martin, AML, (10/03/2020), Jaguar Land Rover, JLR, (13/01/2021) and Hitachi Rail (01/12/2020).

Exploitation of the HyVR process has been discussed with Hub partners, Pentaxia (a HyVR cell for rail vehicle components-25/02/2020) and the PAC Group (infra-red ovens-11/11/2020).

Results/Deliverables/Outcomes

The aim of the feasibility study was to form fibre reinforced thermoplastic sheet material using the HyVR process. A diagram of the HyVR process is shown in Figure 1.

A FRTP sheet is heated above its melt temperature (1) then transferred to the HyVR cell (2). The forming strategy coordinates bulk vacuum forming (DF) (3) with precision robotic forming (ISF) (4) of the FRTP sheet. The completed part is removed from the HyVR cell (5) when cooled beneath the melt temperature.

Objective 1. A cone forming study established the forming limits for the FRTP sheet (continuous and discontinuous). These replicated studies carried out typically with metallic sheets. As shown in Figure 2, while neat TP could be formed (a), it was not possible to use the same method to form a fibre reinforced TP (b). The experimental rig subjects the TP sheet to peripheral clamping. As the fibre reinforcement is inextensible, the FRTP sheet tears when forming. An alternative study using vacuum clamping was able to deform a prepreg sheet material (simulating FRTP at melt temperature) (c).

Objective 2. The optimum forming ISF forming window was determined for continuous and discontinuously reinforced polypropylene sheet at thicknesses of 2 and 4 mm. Samples where heated to 200°C within a conduction oven before manually shuttling to a saw tooth mould at ambient temperature for vacuum forming. Forming was possible for the continuous and discontinuous 2mm and 4mm samples, respectively (see Figure 3). Further research is required to extend the forming period available for a range of FRTP materials.

Objective 3. A lab scale HyVR cell was built. CF epoxy prepreg, chosen to simulate a pliable FRTP sheet, first was formed into single curvature parts. FRTP bridging across the concave mould feature occurred using DF only. ISF was used with multiple, robotically controlled end effectors to overcome the bridging by applying a vertical force. The vacuum level controlled the diaphragm clamping force on the prepreg and was coordinated with the ISF sequence. An iterative forming strategy combining the DF and ISF processes was necessary to achieve success. A generalised HyVR forming strategy was developed to inform the subsequent manufacture of single and double curvature components.

Objective 4. CF epoxy prepreg was formed on moulds with multiple concave features using the HyVR process (see Figure 4a). The quality of these components was equivalent to benchmark parts made by hand layup. Importantly, single curvature forming does not induce reinforcement wrinkling associated with in-plane shearing. CF epoxy prepreg was also formed into double curvature components characterised by a 90° corner that stepped downward a level along a taper (see Figure 4b). Bridging resulting from DF forming was eliminated successfully by applying the HyVR process.

Deliverables

Four deliverables were recorded within the feasibility study proposal as listed in Table 1.

Table 1. List of deliverables from the feasibility study proposal.

Deliverable	Status
Parametric study report on SPIF of composite sheets (in the format of unreinforced thermoplastic (TP), discontinuous and continuous FRTP composites) to characterise the forming limits and failure mechanisms.	Completed via cone study but not successful
An optimal processing window for ISF of continuous FRTP composites of varying textile architectures.	Completed via thermal study
A technical report on the optimised methods for ISF of continuous FRTP composite sheets.	Completed via journal paper
A working setup of a 6-axis robot capable of ISF to manufacture continuous FRTP composite demonstrator parts of complex (double curvature) geometry.	Completed

Outcomes

A journal paper is being prepared for submission in January 2021 relating to the HyVR forming strategy: *M.P. Elkington, P.J. Mistry, M.S. Johnson and H Ou. Hybrid Vacuum-Robotic (HyVR) Forming of Reinforced Composite Laminates. Composites Part A: Applied Science and Manufacturing.*

Future Direction/Impact

A proposal for further funding was submitted to the EPSRC Adventurous Manufacturing Round 2 Call (August 2020, Rejected: 12/10/2020). Fundamental understanding of the non-isothermal characteristics of the FRTP sheet is required. Additional definition of the forming strategy for double curvature component production is needed. Lastly, an over-arching simulation of the HyVR process is necessary. This would raise the technology readiness level (TRL) of the HyVR process from 2-3 towards TRL 5-6. Once this higher TRL is achieved, industrial funding though an Innovate UK proposal would be sought.

A TP themed Hub Core Project is the most suitable route going forward.

The intended impact of a follow-on project is the embedding of the HyVR process within a manufacturing facility for the production of commercial FRTP components. With a focus on lightweighting, the transport sector is targeted. Prior work with Bombardier Transportation (BT) has identified large rail vehicle structures as being suitable for HyVR manufacture. Equally, interest by Lotus, AML and JLR have identified products for manufacture within the automotive sector. These organisations would be engaged in an Innovate UK funding competition.

Synergy with other Hub projects

This project has interacted with The Hub Thermoplastic Working Group whose aim is to generate a thermoplastic core project and applications for external funding. Alignment exists with a Platform Activity in this Group, "Development of rapid processing routes for Carbon fibre/Nylon-6 composites." Particular synergy is evident with the feasibility study, "Incorporation of thermoplastic in situ polymerisation in double diaphragm forming (In-Situ TP-DDF)". The ISF component of this feasibility study links with the Platform Activity, "Tactile sensing of defects during composite manufacture". In effect, the CF prepreg used within this Activity is analogous to the FRTP above the melt temperature.

A future opportunity envisaged is a Hub Core project that draws the activities of the Thermoplastic Working Group together. In particular, the In-Situ TP-DDF feasibility study could be progressed to the next stage through implementation within the HyVR cell. In addition, the prior feasibility study, "Manufacturing Thermoplastic Fibre Metal Laminates by the In-Situ Polymerisation Route", would benefit from the ISF forming capabilities of the HyVR cell. This ISF forming capability equally could be integrated with the 'Fibre Steered Forming Technology' project to assist in forming of double curvature shapes.

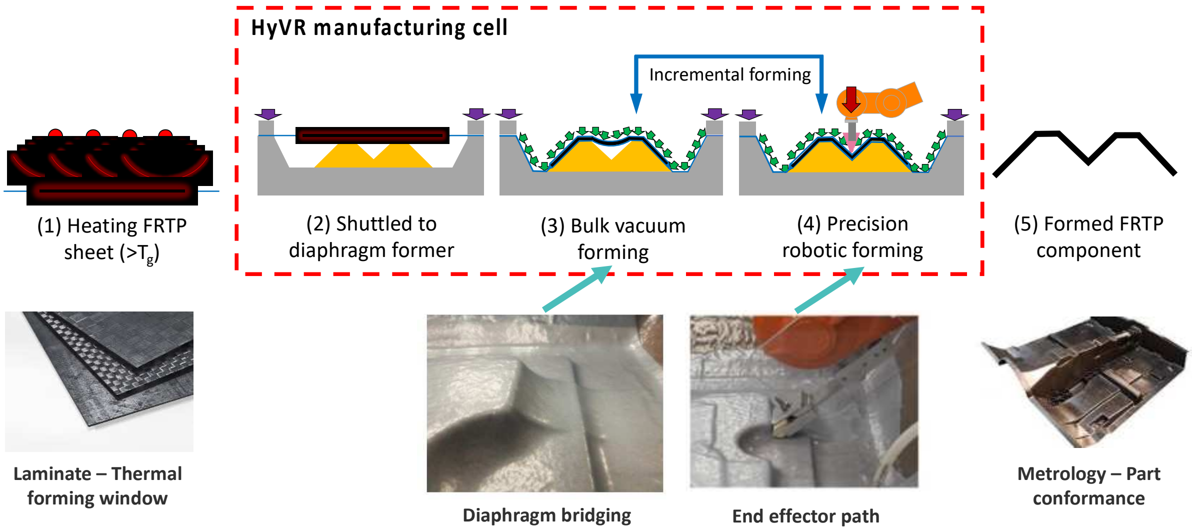


Figure 1. Flow diagram of the Hybrid Vacuum Robotic (HyVR) forming process.

(a) (b) (c)

Figure 2. (a) Formed neat TP with peripheral clamping, (b) Unsuccessful forming of reinforced discontinuous TP with peripheral clamping and (c) Vacuum clamped cone forming study using prepreg sheet to simulate FRTP at melt temperature.

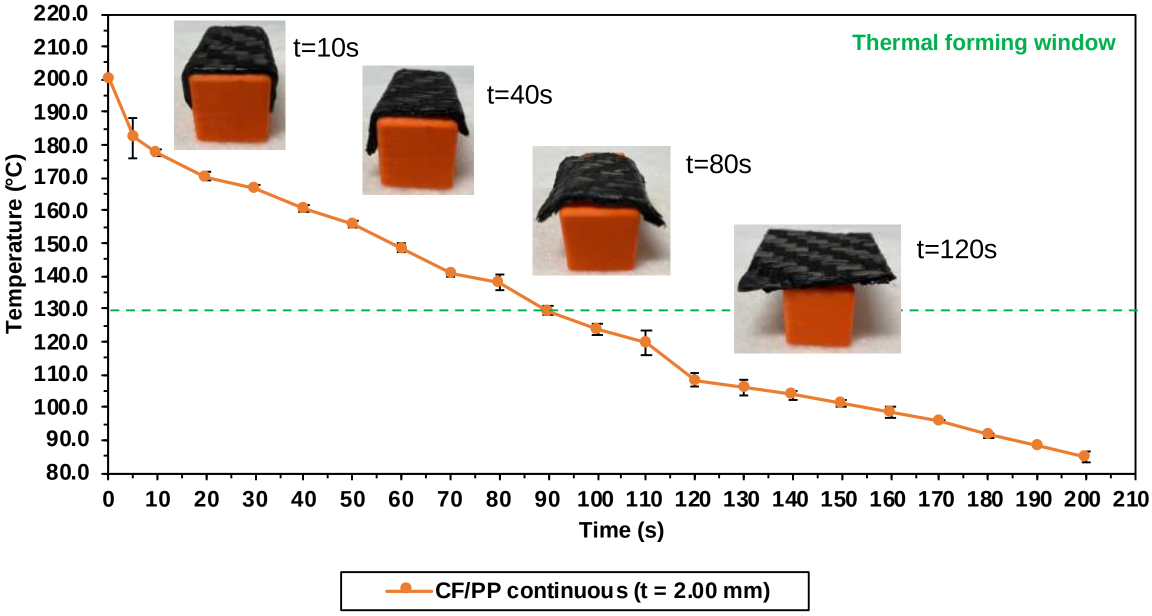
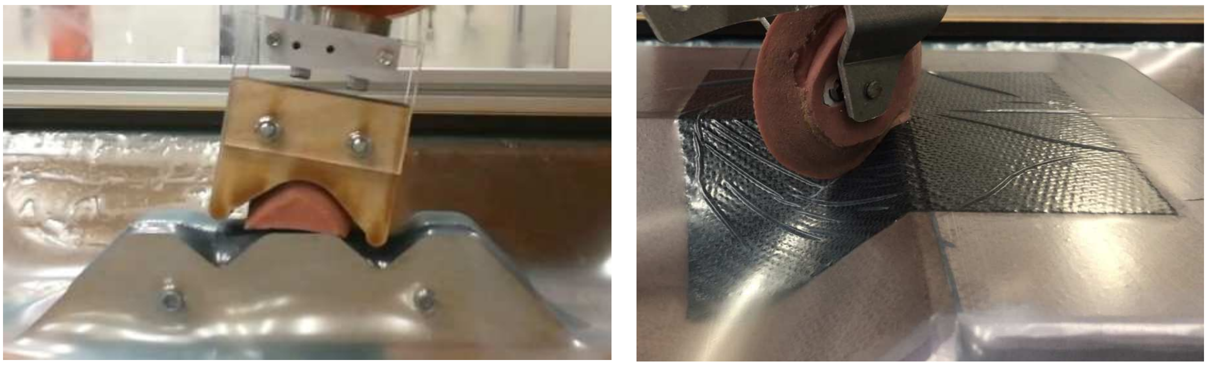


Figure 3. Graph of the continuous CF/PP Temp vs time chart annotated to show thermal forming window with formed specimens at different cooling intervals.



(a) (b)

Figure 4. HyVR forming of (a) Single curvature and (b) Double curvature components.