Feasibility Study (FS) Title: Optimised Manufacturing of Structural Composites via Thermoelectric Vario-thermal Tooling (VarioTherm).

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Partners (include support from Industry): European Thermodynamics Ltd

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Executive Summary:

In this study, the feasibility of using thermoelectric heating/cooling technology to manufacture a vario-thermal tooling system for the optimised processing of thermoplastic composite laminates was investigated. Particularly, the project investigated the heating/cooling performance of commodity thermoelectric (Peltier) modules in a tooling system context, delivered several prototype technology demonstrators and applied these prototype systems to process studies using commercially-available tape-based aligned fibre reinforced thermoplastic laminate materials.

The first prototype tooling system that was developed was built around a single Peltier module (with control system) and showed that peak heating and cooling rates of >3 °C/s were achievable at the tool surface, demonstrating the capability to execute a heat/cool cycle based on PA6-based TPCs in ~100s. The first full tooling system (2 x 2 Peltier array, single-sided tool) was used to process PP-GF60 laminates at 2mm thick, completing a full heat-dwell-cool cycle in <400 s. Measurements taking during these experiments showed a heating/cooling rate of ~1 °C/s was achievable at the laminate mid-plane, limited by thermal losses from the upper free surface inherent to the use of single-sided tooling. A two-sided system was then developed (each side comprising a 2 x 2 array) and applied to perform a modest parametric moulding study on 4 mm-thick PP and PP-GF60 samples. This study revealed that the cooling rate in the system could be sufficiently controlled and adapted to effect measurable changes in relative crystallinity within the PP as determined via DSC.

Background:

Traditional tooling systems for medium/high-volume manufacturing of composites include active heating/cooling to regulate the temperature of the tool, incorporating electrical heater cartridges or a cooling/heating circuit with oil or water as the thermal medium. Most such solutions aim at generating a homogeneous, isothermal temperature across the tool and part throughout a given process (cooling or cure). Moreover, for high-volume manufacturing using thermoplastic composites

(TPCs), conventional tooling technology is suitable only for non-isothermal stamp-forming where part quality can be compromised due to rapid quenching during forming.

This VarioTherm project proposes to use an array of independently controlled thermoelectric (TE) Peltier modules to enable rapid vario-thermal zone heating/cooling in a metallic mould tool. Here, the hot and the cold side of the Peltier can be switched by simply reversing the polarity of the applied DC current offering bulk heating/cooling and accurate thermo-regulation from a simple 'off-the-shelf' thermoelectric module package. Developing this tooling architecture along with the appropriate instrumentation and control system, rapid isothermal processing of thermoplastic laminates was investigated whereby the TPC is optimally-processed at above T_m without the lengthy heating/cooling phases typically experienced during conventional static (melt) pressing [1]. Further, the advanced thermo-regulation capability offered by the Peltier module technology was used to investigate the possibility of controlling the development of the polymer morphology during the cooling phase.

Results:

The three project deliverables were set and achieved. Their main outcomes and challenges will be discussed below in detail against each deliverable.

- **D1:** Prototype construction as a technology demonstrator, allowing a feasibility determination of the proposed technology to a selected application.
- **D2:** Detailed performance data of the system in the context of rapid processing of thermoplastic composites.
- **D3:** A review of the benefits, limitations of proposed zone heating technology as compared to existing tooling technology.

Deliverable 1: The development of the VARIOTHERM prototype tooling systems was performed in a step-wise manner, delivering multiple tooling systems of increasing capability and complexity.

The first stage prototype, the so-called '1-D study', was built to confirm outline feasibility of the application of the Peltier technology and to complete the selection and implementation of the measurement/control system. A single Peltier module was used with an in-house developed PWM control system (Figure 1). Following confirmation of outline feasibility, two further prototypes were developed based on a 2 x 2 array of modules, one single-sided tool **(D1a),** and a double-sided tooling system **(D1b)**. The single-sided tool was built as a viable demonstration of local control of the process and the double-sided tool to evaluate the rapid processing, the necessity of which was determined due to heat losses observed using **D1a**.

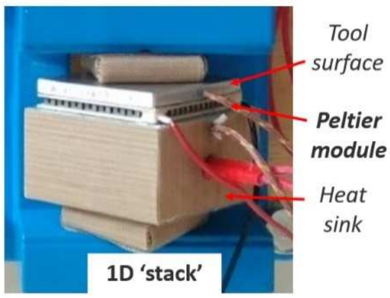


Figure 1: '1-D' VARIOTHERM system

D1a: The prototype was constructed using a 2 x 2 TE module with a flat tool plate of (80 x 80mm), a heat sink (radiator) was attached to the bottom side of the plate with a fan attached below to dissipate heat during cooling (**Error! Reference source not found.**). Thermocouples were mounted on the tool surface and on the radiator.

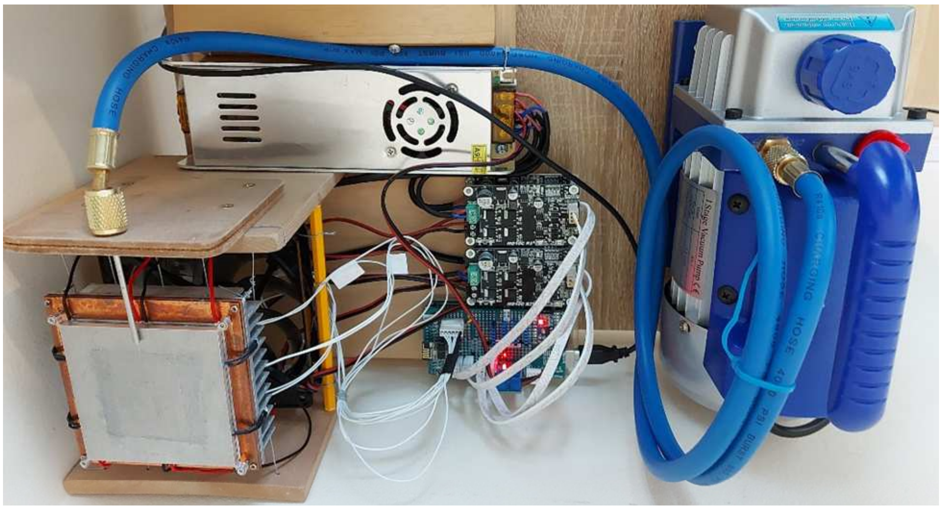
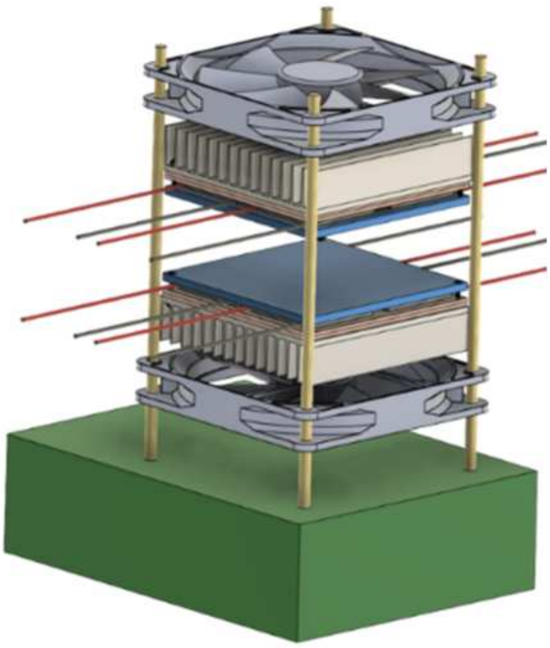
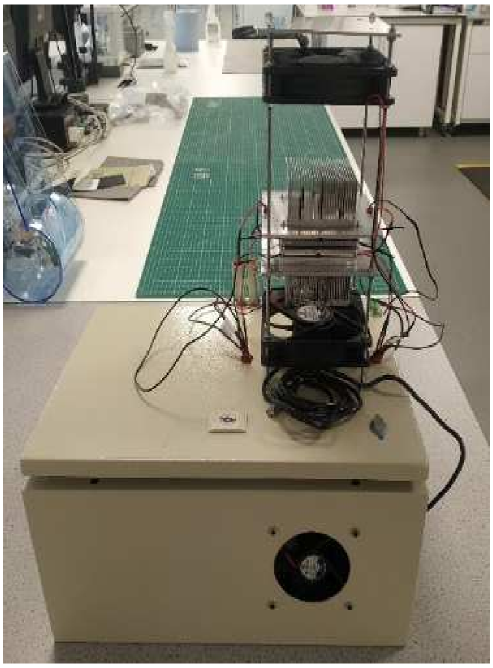


Figure 2: D1a tooling system

D1b: Based on the results from the single-sided demonstrator tool, a double-sided tool was constructed using the same principles (**Error! Reference source not found.**). The prototype consists of a fixed bottom plate tool and a movable top plate tool with radiators and fans at both the plates.

The Peltier systems in both the prototypes were controlled by Arduino hardware, which enables full control over the heating/cooling. The software-controlled system helps in optimising the Peltier system based on the material to be processed.





Deliverable 2: The '1-D' system was run without any TPC material and the heating/cooling and control characteristics were evaluated. Using PA6 processing regime as a target, the system was shown to cool from 240°C to 170°C and heat back to 240°C in ~100s, achieving heating/cooling rates of 1-3°C/s, dependent upon the temperature differential (Figure 4).

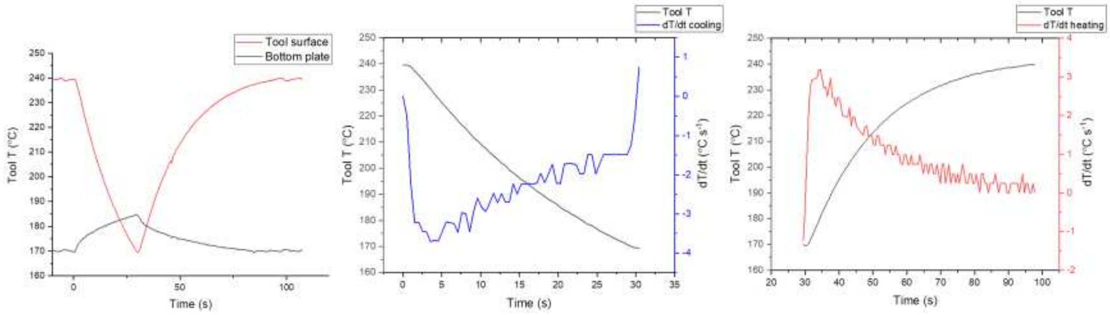


Figure 4: a) Temperature vs. time for tooling system; Temperature and dT/dt vs. time for tool surface, (b) cooling; (c) heating

Prototype D1a was tested with a PP-GF laminate coupon (50 x 50 x 2mm) vac-bagged to the tool

Figure 3: D1b tooling system, a) CAD; b) photograph

surface to investigate the effects of the heating and cooling rates. The processing time calculated was 400 s (≈6.7 min) with a heating rate of 1-2 °C/s (in material mid-plane), and the time taken to reach 200 °C was 150 s. The cooling rate was -1°C/s and time for the cooling was around 160 s. An exothermic change in sample temperature due to crystallization was detected in the cooling phase. A similar outcome was observed with a similarly-processed PA6 coupon, the exothermic peak identified during cooling at a temperature range between 180 – 190 °C corresponding to the crystallisation peak. **Prototype D1b** was used to process the same PP-GF laminate system at a higher thickness of 4 mm. A crystallisation peak (Figure 5) was noted at the temperature range of 120 – 130 °C while cooling the sample from melt, this was confirmed through DSC.

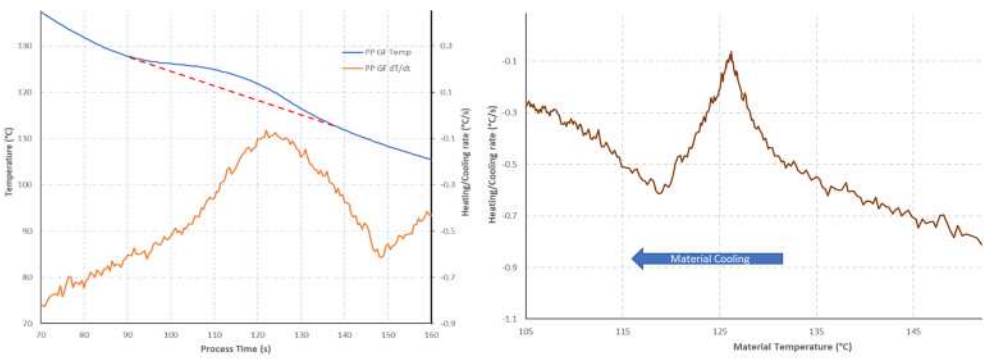


Figure 5: PP-GF cooling using D1b, a) Temperature vs. time; b) rate of heating/cooling rate Vs material temperature

Using **D1b**, PP-GF coupons were cooled at three different rates following melt processing to study the change in morphological structure during cooling. DSC was subsequently performed on these coupons and a change in process induced morphology was seen (shift in melting peaks). As the cooling rates can be easy controlled though Peltier system, it is proposed that degree of crystallinity can readily be optimised in this manner.

Deliverable 3: The Peltier technology as applied to a simple flat aluminium plate tooling system here has delivered typical heating/cooling rates of >1°C/s (peak rates of 3°C/s). A commercially-available proprietary vario-thermal tooling system currently in use at WMG delivers peak vario-therm rates of ~0.6 °C/s. Further, effective temperature regulation using Peltier modules at around the crystallisation temperature could optimise growth of the crystal structures improving the mechanical properties of the sample. This optimisation for a given TPC matrix is now being considered for future projects. The Peltier system at present can operate at up to 250 °C which serves as a limitation against processing performance TPCs. The study successfully demonstrated the feasibly of using Peltier systems as active mould temperature control elements thus opening a window for further studies towards developing and optimising the technology for specific industrial applications.

Outcomes: The developed technology has been demonstrated at a **TRL +3 level** and a joint (WMG and European Thermodynamics Ltd) patent is now being submitted for as well, regarding one aspect of the arising tooling technology, relating to in-situ real-time monitoring of polymer crystallization kinetics during cooling. A journal paper is pending submission (patent submission dependent) that encapsulates the results of the parametric processing study using **D1b**.

Future Direction/Impact

As a result of this FS, WMG HVM-C has sponsored the manufacture of a larger tooling prototype for technology demonstration as part of WMG's National Polymer Processing Centre's TPCs sustainable lightweighting initiative (Peijs et al.). This currently under manufacture at the industrial project partner's premises. Additionally, WMG and the industrial partner have submitted a proposal into the recent May 2021 I-UK Smart Manufacturing call (PIXELTHERM - Precise Next Generation Localised Intelligent-heat control in thermoplastic moulding, Peijs/Reynolds). The technology will also be further explored by WMG through the recently awarded £6m ENLIGHTEN (Enabling Integrated Lightweight Structures In High Volumes) programme led by the University of Twente; an industrially funded project with Van Wees B.V. (Netherlands) on recycling of manufacturing waste of thermoplastic UD tapes; and – project pending – a recently submitted proposal on machine learning assisted recycling of thermoplastic compounds for the EPSRC Sustainable Manufacturing Call.

Synergy with other Hub projects

WMG is currently in discussion with Nottingham University regarding a core-project on TPC for the upcoming Hub call.

1. Reynolds, N., et al., *Direct Processing of Structural Thermoplastic Composites Using Rapid Isothermal Stamp Forming.* Applied Composite Materials, 2020.