Feasibility Study Final Report

Feasibility Study (FS) Title: Additively Manufactured Cure Tooling (ADDCUR)

PI name: James Kratz (PI – Bristol), Maria Valero, Vimal Dhokia (PI – Bath), Elise Pegg

Research staff/students (*include names and % of time*): Arjun Radhakrishnan (20%), Vincent Maes (20%), Max Valentine (40%)

Partners (include support from Industry): Airbus, GKN, LMAT, Rolls-Royce, Surface Generation, and the NCC

Start date: 01-Feb-2022

End date: 31-Jul-2022

Executive Summary

ADDCUR investigated tooling to **reduce embodied energy** of composite manufacturing. Specifically, we explored additive manufacturing to design the lightest possible cure tools to *increase rate and quality* by adjusting the heat distribution in the mould. ADDCUR supports two priority research themes: i) *rapid processing technology* by curing parts in half the time, and ii) *design for manufacture via validated simulation* by eliminating costly tool modifications that slow product development time.

This feasibility study has demonstrated potential to control composite curing with AM tooling to a level that is unachievable by conventional machining methods. We found that the exothermic overshoot due to curing heat released by the epoxy appears to be proportional to lattice density, while the heating rate due to the low thermal conductivity of polymers was more sensitive to the facesheet thickness. The potential to spatially match the tool properties to the composite part is possible. How this is applied to industrially relevant cases requires further work.

Background

Cure tooling is often an afterthought but is a major non-recurring cost with long lead times and can become a recurring problem. There are no *design for manufacture* workflows for effective single iteration design of complex manufacturable tooling optimised for energy efficiency. Currently, an AM ‘clean sheet design’ will require between 7–10 design iterations, often taking months. The approach here has the potential to radically shorten the design to manufacture time of complex tooling, targeting single iteration designs at a considerably lower cost.

The following objectives were addressed:

O1) Develop a Design for AM workflow for composite cure tooling.

O2) Evaluate stainless steel AM cure tools for composite moulding requirements, such as surface finish, vacuum bag sealing, and thermal responsiveness.

O3) Demonstrate energy savings of AM cure tooling during the manufacture of composite parts with industrially relevant features.

Feasibility Study Final Report

Results/Deliverables/Outcomes

A design for AM workflow was defined linking together, simulation, design and manufacture specially for the generation of tailored AM composite cure tooling. A typical monolithic cure tool was broken down into a facesheet and lattice. Backing structures were not considered at this TRL. Through the evaluation of the lattice geometries and facesheet thickness, it serves to inform decisions relating to the lattice properties to achieve the desired tooling requirements for complex composite geometries. The work serves to help provide the necessary information to design the lattice volumes by understanding how different lattices behave. Example lattices are shown below in Fig. 1. The tool stiffness was quantified with finite element modelling using ABAQUS software.

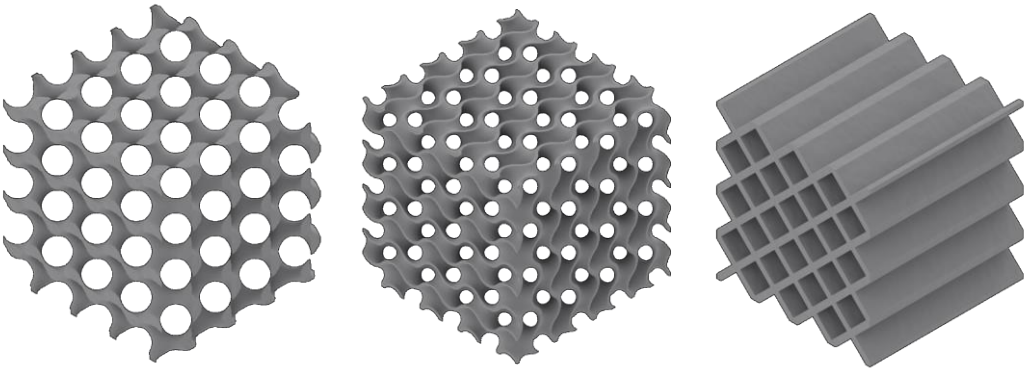

Figure 1. Lattices (*l*–*r*) of the repeated gyroid, dual-wall gyroid, and planar diamond.

A total of thirty flat tools were manufactured out of 316L Stainless Steel (SS316L) powder using a Renishaw AM250 L-PBF machine. Some tools were exceptionally light, having a lattice volume density of 7% and a facesheet thickness of 0.75 mm. The as-printed surface had a roughness of Ra 10 microns. Before laying up the composite prepreg laminates, light grit sandpaper removed any partially sintered powder particles from the layup surface and the tools were cleaned. There was no additional post-processing of the tools after removing the support structures from the bottom surface.

The thermal responsiveness of the mould tools was measured by oven curing a prepreg (MTC400-C415T-T700-12K-38%RW-1250) from SHD Composites using vacuum bag only pressure. The composite laminate was prepared using fourteen plies measuring 40 mm x 40 mm to form a theoretical cured thickness of 7 mm. A thermocouple was placed within the prepreg stack right between the seventh and eighth plies to capture the thermal history. A target oven heating rate of 3 °C/min was applied and a cure temperature of 135°C for 1 h. The tools were found to achieve a hard vacuum (50 mbar) and also pass a standard aerospace leak test (no noticeable drop in 5 minutes on an analogue gauge).

The thermal responsiveness of the mould tools is shown in Fig. 2. The tools with thinner facesheets allowed for a faster heating rate as there was less material for the environment to heat up before reaching the composite. The tools with slower heating rates and therefore greater thermal mass were able to mitigate the overshoot effect, leading to smaller overshoot temperatures on the thicker and heavier tools. This indicates that the overshoot appears to be proportional to lattice density, regardless of the plate thickness, while the heating rate was more sensitive to the facesheet thickness.

Feasibility Study Final Report

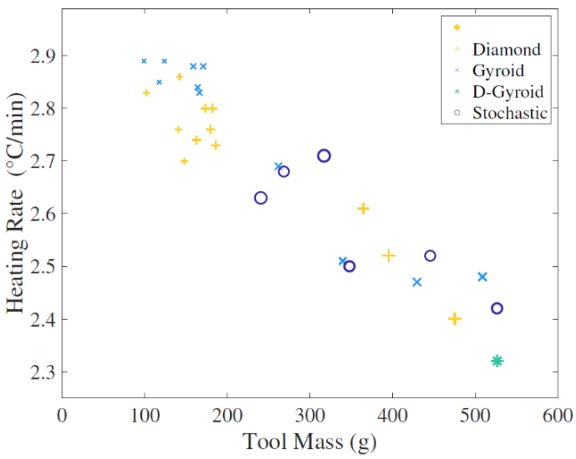

Figure 2. Thermal responsiveness of AM mould tools.

To compare the AM mould tools to conventional tooling, the semi-complex part shown in Fig. 3 was manufactured. The optimal lattice structure was chosen from Fig. 2 and the same materials as above. An equivalent part was manufactured using solid 8 mm thick stainless steel tooling. Even though the curing cycle was not optimised, a 50% energy reduction was measured. A larger exotherm was measured in the part manufactured on the AM tooling, in agreement with the observations shown in Fig. 2. There is room to trade-off exotherm by increasing cure cycle time.

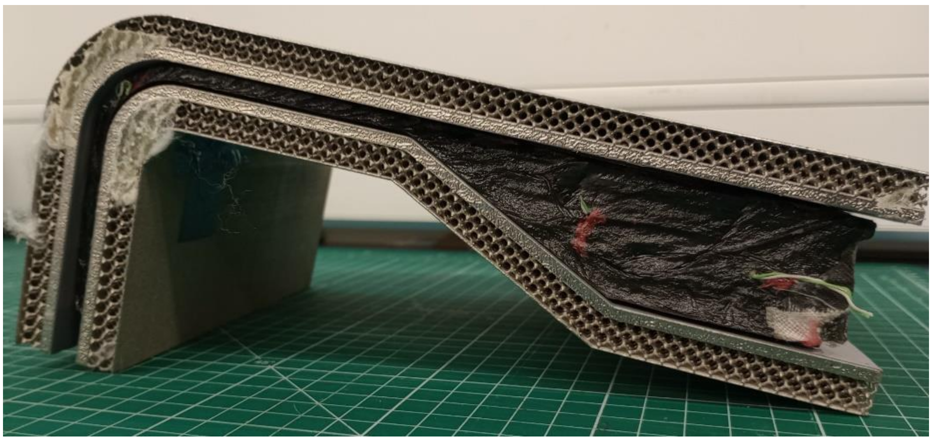

Figure 3. Semi-complex part made using AM tooling.

Future Direction/Impact

This feasibility study has just scratched the tip of the iceberg of what is possible with AM cure tooling. While tooling has been identified as a priority to help the UK develop capability to digitally design and deliver future composite products, further challenges need to be overcome. Some non-exhaustive topics include: dimensional stability, size of mould tool, tessellation and joining of different tooling segments, lead-times, and in-process monitoring and control of temperature. Developing these approaches could have significant impacts on the UK mould tooling and composites sector. We are working with one of our partners to explore some of these concepts.

Feasibility Study Final Report

Synergy with other Hub projects

A Synergy proposal was submitted after the February 2022 workshop but was politely declined by the Hub.

Please complete the table below:

		Target / project	Actual achievements
	Project duration (yrs)	0.5	0.5
	Project Value (80% FEC)	£ 50,000	£ 50,000
Project Metrics	**PhD students**	0	0
	PDRAs (FTE per year)	1	1
	Person years	0.5	0.5
	Project based partners	1	6
	Institutional support	£ -	£ 15,000
	Industry support (Letters of Support)	£ 12,500	£ 12,500
	Additional leveraged grant income	£ 125,000	£ 15,000
	Additional industry leveraged income	£ 60,000	0
	Journal publications	0.5	2
	Conference papers	1	2
	Patent applications	0	0
	New collaborative research activity	0	0