Feasibility Study Final Report

Feasibility Study (FS) Title: Microwave in line heating to address the challenges of high rate deposition

PI name: Prof Richard Day, Wrexham Glyndwr University (WGU), Dr Betime Nuhiji , University of Sheffield (UoS)

Research staff/students (*include % of time*): Dr Nataliia Luhyna (WGU), Dr Asimina Manta (UoS)

Partners (include support from Industry):Wrexham Glyndwr University/University of Sheffield AMRC/ BAe systems

Start date: 1st August 2019

End date: 31st December 2020

Executive Summary

The purpose of the study was to explore whether microwave heating could be used during automated fibre placement as a method of increasing the layup rates to the 100 kg/hour requirement, which would enable further use of composites in a range of structures, particularly, but not exclusively aero structures. This fits into two of the Hubs priority areas

1) High rate deposition and rapid processing technologies
2) Design for manufacture via validated simulation

This project is complementary to the core project on the technology framework for automated dry fibre placement and fits within the high rate deposition and rapid processing technologies research priority area in the call.

Potential microwave cavities simulated using COMSOL and HFSS software, where two of these were developed in the laboratory. One was, as expected, not suitable due to its size and performance although it was used to trial data for use in validated simulations. The second cavity, a truncated waveguide section, performed well. Simulations of heat up rate in this cavity as well as practical measurements showed that it heated at rates which would be able to hit the target layup rate of 100 kg/hr

The research question was successfully answered. There is mileage in this approach which shows that a practical microwave system of heating during automated layup is possible and desirable. Furthermore it may be possible to combine this with other forms of heating to produce very significant layup rates.

Background

The aim was to study potential microwave techniques for increasing the throughput for placement of thermosetting and thermoplastic tows to increase the rate of automated tow placement and filament winding. To achieve this, there was a need to produce processes capable of placing 100 kg/hour.

Results/Deliverables/Outcomes

Three challenges were faced during the work;

1: Retirement of the Co-I at Bristol meant that access to the AFP equipment did not materialise. To mitigate against AFP availability, bespoke equipment was manufactured in house at WGU to simulate the process and evaluate heating and layup rates. It also meant that the tape was scaled down to 8mm which could be handled in the space available.

2: Due to resignation of the person expected to undertake the modelling work the PI picked this up in the interim while a replacement was trained who then took over.

3: Covid19 meant that the labs were out of bounds for seven months leading to very long project delays and the loss of some of the materials to be trialled.

Nevertheless, with some modifications of the programme to build a rig to simulate the process on a lab scale, the majority of the aims of the work were achieved and deliverables met.

Objectives

1. To develop microwave cavities suitable for in line heating of tows at 2.45 GHz and to couple to an existing 2 kW microwave system

Three cavity designs were identified and modelled using COMSOL and/or HFSS. A whispering gallery mode cavity and truncated WR9a waveguide section were identified as the most promising of these. Both designs were used for practical measurements. Further simulation showed the truncated waveguide was the most promising as did the laboratory trials. Given the high heating rates observed, the power was, however, limited to 200 W for the static tests and the rig to simulate the AFP process. Potential heating rates in the waveguide from simulation and measured heating rates in the laboratory showed that the target layup rate could be achieved with a power of 5 kW, similar to that used in diode laser heating systems.

This objective was achieved, although at a lower power for safety reasons.

2. To assess the potential heating rates achievable on narrow static tows in the laboratory using a sealed system.

Heating rates were evaluated in the laboratory at 200 W using static tows where processing temperatures increased within one second in the truncated waveguide cavity. The whispering gallery mode cavity took 30 s to heat the CFRP tows and was not used for further work, but rather to verify materials data used in the simulations. Static experiments were not conducted at 2 kW since the heating rate would have been too high to monitor the temperature rise and would have resulted in rapid thermal degradation of the material. The highest rate observed was 150^{O}C/s at 200W which would correspond to throughput of approximately 2kg/hr at 2kW for PEEK/CF. This is unsurprising as the dielectric properties of PEEK are very low. Simulations showed a very similar result, also that with a change in geometry of the cavity higher heating rates are possible. Simulations of a typical epoxy/carbon material showed that around 30 kg/hr could be laid up at 2 kW. Using a power of 6kW, similar to diode lasers used currently, layup rates close to the target could be achieved. Since the materials had cured during the shutdown due to COVID 18 this could not be tested in the laboratory.

This objective was achieved.

3. To investigate designs of microwave choke or screening to ensure that the microwave radiation is contained during processing with conductive fibres.

Feasibility Study Final Report

Models of the selected microwave cavity were assessed using the electromagnetic simulation software HFSS. These showed that while most leakage could be prevented, complete protection was not possible within the constraints of also fitting into the space available in a fibre/tow placement head. Practical assessment in a Faraday cage showed leakage beyond acceptable limits (10 mW/cm^2) occurred when powers above 20 W were used. Hence all the practical work was carried out within a Faraday cage. This is not seen as a show stopping result as diode laser heated systems also require a full cage around them and indeed, with the right design of microwave system the two are compatible which could lead to extremely high rates of layup. While the simulations showed a significant reduction in the extent to which microwaves are present in the area around the cavity when a choke was used, there were still significant areas of concern where the voltage gradient exceeds the action level in The Control of Electromagnetic Fields at Work Regulations 2016.

This objective was achieved in that the modelling showed that a choke would not be practical in an AFP system because it would need to be very large to work and a Faraday cage would be the best solution.

4. To conduct simple trials at UoB to assess the potential of the microwave system in enhancing the lay down rate of wide (100 mm) tape.

Access to equipment at UoB was not available and so a rig to pass 8 mm tape through a microwave cavity operating at 200 W was manufactured at WGU. This showed that the process was feasible.

This objective was modified in light of the circumstances and the amended objective was achieved.

5. To consider methods for increasing the power delivered in follow on projects.

Other designs were explored in the project. The two most promising are the truncated waveguide and an open horn applicator. The latter would be compatible with a combination of microwave and diode laser heating. Radio frequency (RF) systems were also considered, but not within the scope of the current project. Likewise there are now microwave transistors which are more flexible in practice, but lower power than traditional sources which will be explored in a follow on project.

<u>Deliverables</u>

a) A laboratory assessment of the heating rates/deposition rates achievable using up to 2 kW microwave power for different types of tow at 2.45 GHz (WGU)

The high heat up rates experienced in the laboratory and observed in the simulations meant that the static heating experiments in the laboratory were limited to 200 W. These showed that at 200 W PEEK/CF tows could heated to temperature in about 2.5 seconds, although there were significant delays in the heat transfer to the temperature probe. and Simulation showed that the actual heat up time to the melting point is c.1 s. Potential deposition rates were estimated to be ~ 5 kg/hr at 2kW for PEEK/CF. Assessments of the heating rate for epoxy systems could not be undertaken for epoxy/CF as these prepregs cured during the COVID 19 lockdown, but simulations showed the target lay down rate was achievable with these materials.

This deliverable was met.

b) Cavity and mounting system to be used for trials on an existing 2 kW 2.45 GHz microwave system (WGU and UoS)

Since the system was not available, this deliverable was modified to be a cavity and mounting system for a laboratory based rig.

This deliverable was met.

c) Evaluation of potential shielding/choke approaches for the AFP system at Bristol (UoS)

Approaches to modifying the cavity to provide a choke were explored using computer simulation but found to be impractical within the constraints of a practical AFP system. Hence a faraday cage was used in all work and will be used in future developments.

This deliverable was met.

d) Numerical model of the process (UoS)

Numerical models of the process were developed at UoS (using COMSOL) and also at WGU (using HFSS). These gave identical results and in particular transient analysis showed that a rate of approximately 32 kg/hr at 2 kW is attainable using a carbon fibre/ epoxy tape. This leads to an assessment that the target laydown rate could be hit using similar powers to those used in diode laser systems. The models showed electrical breakdown would occur at much higher powers.

This deliverable was met.

e) Demonstration of process using laboratory AFP at the UoB(WGU, UoB)

The deliverable was modified since the original equipment was not accessible. Instead a 200 W rig was built and the process was demonstrated in the laboratory.

The modified deliverable was met.

Future Direction/Impact

The work undertaken to date is positive; the simulations and experimental work all point to this being a viable process. There are further potential sources of heating which should also be followed up including RF as well as microwave heating using both existing and recently developed microwave transistor technology. Having established that there is potential in this work, the next stage forward is to fully evaluate other potential sources of electromagnetic heating before finalising a design to be trialled on a full AFP system. The University of Sheffield have identified an AFP which could be used for the trials and it has diode laser heating fitted alongside a large double metal skinned box as a result. A Hub Core project is the most suitable route for development by further screening potential solutions then applying the most promising to an existing, identified AFP setup.

The follow on project has the potential to provide a step change in layup rates, either on its own or combined with laser heating, hence the potential impact is global. The project has the interest of BAe systems; their specific needs will be accounted for in the proposal.

In the meantime a rig to evaluate the process at 2 kW is being built at WGU as an intermediate step. A microwave cavity to operate at 5.8 GHz is being manufactured to work in the existing rig since BMI resins (which BAe are interested in), heat more efficiently at this frequency. Hence we expect a total of three publications to come from this case study eventually, as well as social media coverage and a core project to move to a demonstrator facility.

Synergy with other Hub projects

There is overlap with other work at Bristol and Southampton now part of a Synergy project looking at residual stress and temperature development during microwave cure.

There is potential for collaboration with University of Nottingham and Bristol University since both are working on AFP projects and Nottingham have a project on direct heating.

Discussions have taken place with Brunel University to further explore the M Cables project using the expertise at Wrexham Glyndwr University in antenna design to improve the uniformity of the heating. Also there have been discussions with Nottingham University to use this approach in over moulding of organofilms.