Microwave (MW) heating through embedded waveguides for composites manufacturing: A feasibility study

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Summary: The feasibility of utilising MW heating for composites manufacturing without the need of a dedicated MW Oven is the topic of this report. The initial concept of wires with slots that will act as MW applicators (waveguides) did not produce an acceptable thermal profile: local temperature variations were too high. The simple configurations tried in this study improved the local variations, but more work is needed to conclusively evaluate the idea and its practicality. A different approach was then tried: MW applicators that can be realised as printed circuit boards (PCBs). These boards can be slotted inside tooling. Their design can follow the heating requirement of the composite shape and size. The feasibility study showed that the PCB applicators fulfil two of the three concept feasibility criteria. The concept was validated by producing a number of composite laminates that were of similar quality to laminates produced in a convection oven.

Introduction: When a carbon fibre composite is heated through MW radiation, electromagnetic (EM) energy is absorbed by the carbon fibres and converted to heat. The heating process is volumetric and instantaneous. The resin matrix is subsequently heated through conduction.
There are three fundamental components in MW heating [1-2]:

- MW source: Usually a magnetron, which is a resonant cavity used for the generation and amplification of the EM signal. Other sources are voltage-controlled oscillators coupled to travelling wave tubes (TWT) or solid state sources.
- Transmission lines: Waveguides and/or coaxial cables used to couple the source with the load. The selection of the transmission line is based on the applied voltage and current. Rigid or semi-rigid coaxial cables are often used
- Applicator: The radiating element used to transmit the MW radiation to the absorbing medium (in this case, the carbon fibres). Applicators can be waveguide apertures or separate antennas.

The interaction of MW radiation with the carbon atoms at molecular level is macroscopically described by the dielectric properties of carbon.
As the EM energy is converted to heat, the EM field magnitude decreases with increasing distance from the absorbing material surface [1-4]. The penetration depth, *d*, is defined as the distance from the surface at which the EM wave power decrease by a factor of *1/e*. The penetration depth is a function of frequency [1]:

$$D_p = \sqrt{\frac{1}{\pi \cdot f \cdot \mu' \cdot \sigma_{ec}}}$$

In the above equation, f is the frequency [Hz], μ' is the real magnetic permeability [H/m] and σ is the electrical conductivity [S/m]

Materials: A 600g/m^2 continuous carbon fibre epoxy prepreg by Gurit (SparPreg^{TM}) was used for the tests. The ply thickness was about 0.6mm. The manufacturer recommended cure cycle for the prepreg is about 60 min dwell at 120°C [5]. Multi-Ceramic Technology LLP supplied MCT255 cordierite ceramic which was used as tooling material.

Experimental setup: The laminates produced for the feasibility tests consisted of 4 plies. The laminates dimensions were 300mm by 300mm by 2.4mm. N-type thermocouples were placed in between the plies in order to record temperature distribution. Figure 1 shows the experimental setup and the location of the thermocouples between the plies.

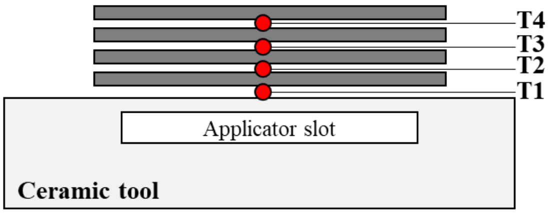

Figure 1: Experimental configuration

An Industrial Power Systems GU020 magnetron power supply, rated at 2kW was used as the microwave signal source and amplifier. The signal frequency is 2.45 GHz. The output of this microwave source comes coupled with a rectangular WR340 aluminium waveguide. A directional coupler and a tuner mounted on the waveguide are used for measuring and modifying the reflected power. The setup is shown in Figure 2.

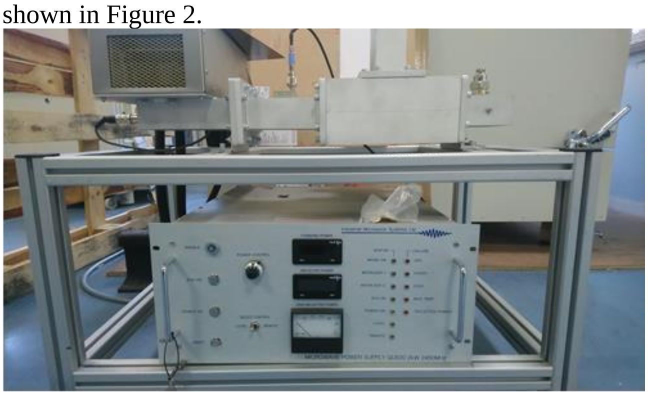

Figure 2: Industrial Power Systems GU020 magnetron, rated 2kW @2.45GHz. The magnetron, rectangular waveguide, directional coupler and filter can be seen on top, while the measurement and control equipment are visible on the lower part of the photo

Coaxial cables (HUBER+SUHNER - SUCOFLEX 106) with N-type adaptors were used to couple the magnetron waveguide output with the radiating element. This is a 50 Ohm type of cable, rated for frequencies up to 18GHz. A combination shielding type (aluminium tape and braid) is

used for protection from potential microwave leakage through the transmission line.
The radiating elements were manufactured by TrackWise Ltd using double copper-clad (2oz) printed circuit boards (200x300mm). The substrate used was commercial FR4 with 1.6mm thickness. Two different types of radiating elements were manufactured and tested, a monopole array and a fractal antenna. The applicator was placed beneath the composite sample, with a PTFE or ceramic layer in between. The temperature on the surface of the carbon fibres during testing was measured using Optocon optical fibre temperature sensors.
A handheld FLUKE Ti25 IR thermal camera was used for temperature measurements at the surface of the composite.

Initial tests using coaxial cables: Coaxial cables with a number of different slots have been tried in order to assess the temperature distribution that can be achieved. In order to test the different configurations a test-box was manufactured. Carbon fibre prepreg was wrapped around a ceramic core. Holes were machined in the ceramic for cables to be slotted in and tested quickly. Experiments with and without thermocouples were performed in order to establish that the presence of thermocouples did not affect the heating of the composite. Figure 3 shows the experimental setup and corresponding thermal images.

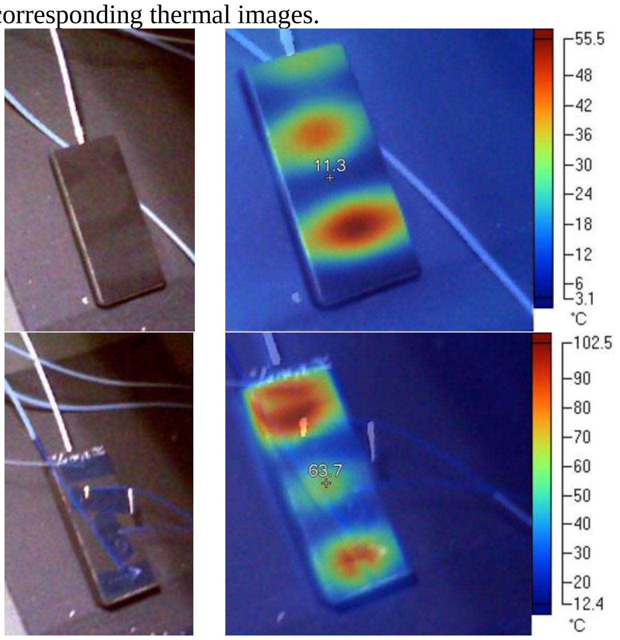

Figure 3: Slotted wires test setup and corresponding thermal image

Table 1 shows some of the slot configurations tried. The temperature distribution is measured as $\Delta T = T_{max} - T_{min}$.

Table 1: Slots configurations tested and ΔT achieved

Slit shape	Dimensions	Inclination	Period	ΔT (°C)
	a = 8 mm b = 2 mm	0°	1 cm	25-55
	a = 8 mm b = 2 mm	45°	1 cm	25-40
	a = 8 mm b = 2 mm	90°	1 cm	30-50
	d = 5 mm		1 cm	15-25
	d = 5 mm		2 cm	45-70

From these tests it became apparent that a combination of slotted cables could not achieve the targeted uniform temperature distribution unless a full spatial optimisation exercise is conducted and complex configurations are tested. Hence an alternative approach was tried in order to test the feasibility of the concept.

New applicator design & modelling: The applicator consists of a copper Printed Circuit Board (PCB) on which monopole or dipole antenna elements and their feeds have been etched. FR4 (1.6 mm thickness) was used as a grounded substrate. A dielectric barrier of variable thickness and dielectric constant is placed between the PCB and the composite part to protect the applicator, but also to effectively act as a tuning element by modifying the load impedance. Due to the very small distance between the applicator and the absorber, a reactive, near-field type of radiation is dominant.

A composite laminate was used for the modelling exercise. A homogenous and isotropic material approximation was used. For the initial simulations the effects of fibre orientation and stacking sequence were not taken into consideration, as such complexity would result in demand of high computational resources. The coupling with the magnetron source was modelled as a lumped port with variable power input and frequency.
The problem was solved in the frequency domain. The loss distribution in the carbon fibres was derived using the Ansys Electromagnetic Suite v.2017 [6]. The total amount of generated heat was calculated as the volume integral of the losses inside the composite part. The optimization goal for the design was the maximization of the radiating element efficiency, defined as the heat to input power ratio, as well as the uniformity of the heat distribution inside the composite. The resulting designs along with a visualization of the simulation results for the heat distribution can be seen in Figure 4. The actual applicator that was constructed for the tests is shown in Figure 5.

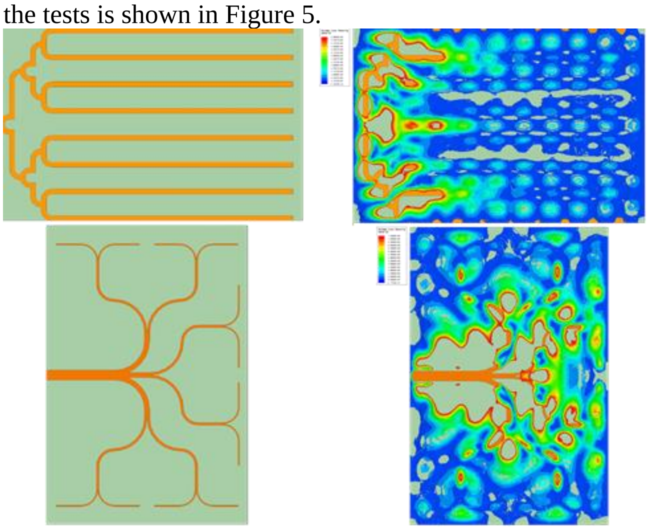

Figure 4: Monopole array (top) and fractal (bottom) radiating element designs. A visualization of the resulting loss distribution derived with Ansys High Frequency Field Solver (HFSS) can be seen on the right for the two designs

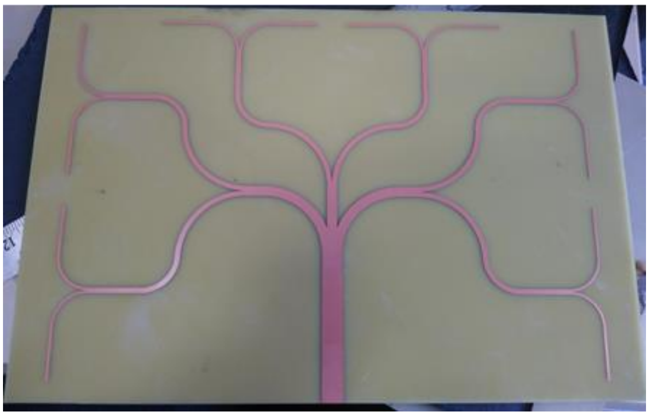

Figure 5: Fractal antenna used as a microwave applicator. The antenna feed where the coaxial cable is coupled is visible at the bottom of the photo.

Results: The temperature distribution of the laminate during cure using the new MW applicator is shown in Figure 6. Thermocouples closer to the tool surface follow the cure profile more accurately. The MW power was controlled manually. Full power (2kW) was supplied at the beginning until temperature at thermocouple T1 reached 120°C. Then, it was manually adjusted in order for the temperature of thermocouple T1 to be kept within ±0.5°C of the dwell temperature. The temperature between the layers further from the tool surface was lower. The temperature difference between T1 and T4 thermocouples was about 10°C at the isothermal segment.

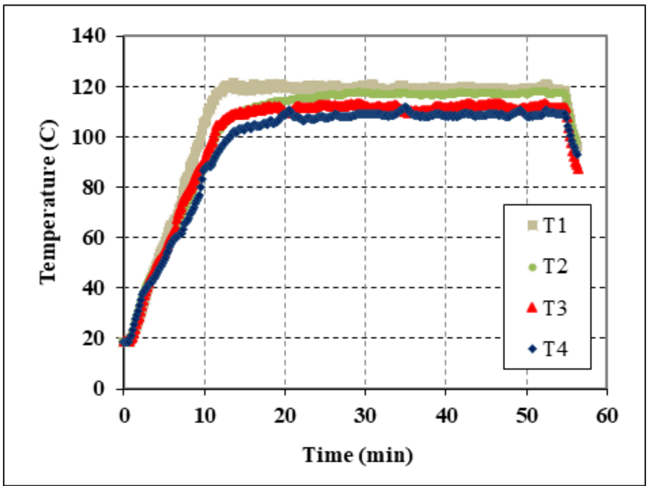

Figure 6: Temperature distribution of laminate cured using the new MW applicator

The temperature distribution of the laminate during cure using the same tool but no MW applicator in a convection oven is show in Figure 7.

In order to assess the potential for energy savings we performed a simple analytic calculation of the energy required to heat the composite from ambient to 120°C. The analytic calculations are provided in the Appendix. Table 2 summarises the results. The potential energy savings are 68%. Conduction from the composite part to the tool and the surrounding air is not considered in the calculation, therefore the practical energy savings will be lower. Energy savings will also depend on tool and part size.

The heating rates achieved during MW heating and conventional oven heating are calculated in Table 3.

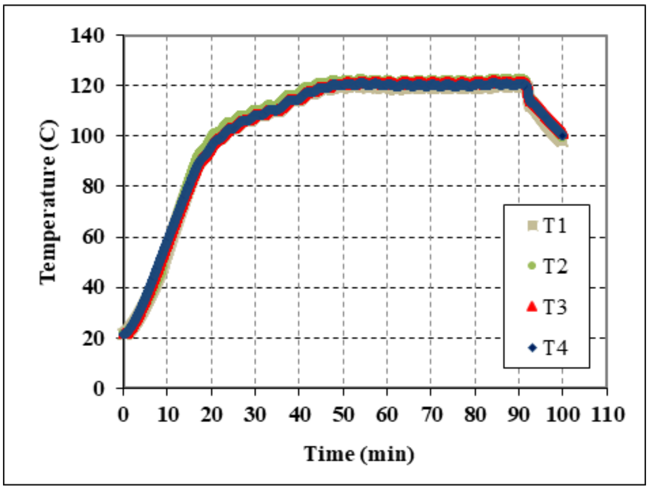

Figure 7: Temperature distribution of laminate cured in oven

Table 2: Potential energy savings

	MW heating	Convection oven
Air inside the oven	0 kJ	61 kJ
Tool	0 kJ	32 kJ
Composite part	44 kJ	44 kJ
Total energy:	44 kJ	137 kJ

Table 3: Heating rate calculation

Heating method	t/c	$T_{t=0\ min}$	$T_{t=10\ min}$	Heating rate
MW heating	T1	20°C	105°C	8.5°C/min
MW heating	T4	20°C	89°C	6.9°C/min
Convection oven	T4	20°C	59°C	3.9°C/min

The glass transition temperature, T_g, from four locations of the same laminate cured using the new MW applicator was measured using a Perkin Elmer DSC 6000. The same measurement was performed in the laminate cured in the oven. For all samples, a second ramp provided the T_g of the fully cured sample. The ratio between the initially measured T_g and the final T_g for each specimen was used to estimate the degree of cure, α. The results are shown in Table 4.

Table 4: T_g and degree of cure evaluation

MW heating				Oven cured			
ID	T_g	$T_{g,f}$	α	ID	Tg	$T_{g,f}$	α
A1	98	112	0.88	B1	105	110	0.95
A2	108	111	0.97	B2	106	111	0.95
A3	107	111	0.96	B3	105	109	0.96
A4	108	110	0.98	B4	105	112	0.94
Average T_g			105	Average T_g			105

Discussion & Feasibility assessment: The assessment of the feasibility study is summarised in Table 5 using the criteria for feasibility, demonstration and validation as set out in the M-CABLES proposal.

Two of the three feasibility criteria have been met. The potential for energy savings is much higher than the envisioned 25% although the accurate assessment will depend of the materials chosen and size/shape of the composite part. The heating rates achieved in the manufacturing trials were between 6.5°C/min and 9°C/min, surpassing the initial target of at least 5°C/min. The temperature distribution achieved was ±10°C, not reaching the ±5°C target set at the start of the study. The small penetration depth of MW heating through carbon fibres does mean that after a few millimetres the dominant heat transfer mechanism is conduction, although there have been indications from prior work that joule heating of the carbon fibres could heat up the resin matric surrounding the fibre [6]. Several factors could be further investigated in order to assess how close to the target this technology can get: Use of pressure to consolidate the plies for improved conduction, examination of the influence of ply orientation in how the MW energy is distributed in the composite and use of close tool where suitable MW applicators can be located on both sides of the composite.

The demonstration criterion has been met. Laminates of thickness around 2.6mm have been manufactured using hand layup and vacuum.

The validation criteria have been met but not fully. Three out of the four samples extracted from the laminate produced using the new MW applicator had a T_g of 108°C while the T_g of the oven cured laminate was 106°C. However, one sample shown a lower T_g (98°C). The degree of cure for both laminates was evaluated as the ratio $T_g/T_{g,\text{ fully cured}}$. Both laminates shown degree of cure higher than 95%.

Table 5: Feasibility study assessment

Concept Feasibility	
Criteria	**Assessment**
Temperature distribution within ±5°C	ΔT = ±10°C achieved
Energy savings of 25% compared to conventional heating	Potential is there. Savings will vary on case by case
Achievement of heating rates >5°C/min	Heating rates ~8°C/min achieved
Concept demonstration	
Criteria	**Assessment**
Manufacturing of composite laminates	Laminates manufactured
Concept validation	
Criteria	**Assessment**
Laminates with uniform T_g (±2°C) and uniformed cured (>95% across the laminate)	¾ samples from the same laminate within the limit. One point outside the ±2°C threshold

References

[1] A.C.Metaxas & R.J.Meredith, "Microwave Heating" (vol.1), Peter Peregrinus ltd, London, 1983

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[2] W.I.Lee & G.S.Springer, Microwave curing of composites, *J Compos Mater* 1984; 18(4):387-409

[3] J.Mijović J & J.Wijaya, Review of cure of polymers and composites by microwave energy. *Polym Compos* 2004; 11(3):184-191

[4] Gurit. SPARPREG Datasheet. 2012

[5] https://www.ansys.com/en-gb/products/electronics

[6] M.Kwak, "Microwave Curing of Carbon-Epoxy Composites: Process Development and Material Evaluation", PhD thesis, Imperial College, London 2016

Appendix: Energy savings calculations

A1: Problem definition and assumptions: We assume an oven, tool and composite. For the MW heating case, the tool and the air do not heat up, apart from cooling of the composite part to its surroundings.

The following assumptions are made for the calculation:

- The air, tool and composite inside the oven are all at the same temperature. There are no temperature distributions or gradients
- No energy loses to the air surrounding the oven are considered.
- The oven is a closed system (no air escapes or enters the chamber)
- The oven mass is excluded from the calculations
- Energy loses due to thermal expansion and/or reaction are omitted
- Material parameters such as density and specific heat capacity are constant throughout the cure. Average values are taken in order to estimate the energy requirements for the process
- The ambient temperature remains constant

A2: Parameters definitions

Composite part

Parameter	Definition	Units
vf	Fibre volume fraction	-
m_r	Resin mass	Kg
p_r	Resin density	Kg/m^3
$c_{p,r}$	Resin specific heat capacity	J/Kg.K
m_f	Fibres mass	Kg
p_f	Fibres density	Kg/m^3
$c_{p,f}$	Fibres specific heat capacity	J/Kg.K
V_p	Composite part volume	m^3

Tool

Parameter	Definition	Units
m_t	Tool mass	Kg
p_t	Tool material density	Kg/m^3
$c_{p,t}$	Tool material specific heat capacity	J/Kg.K
V_t	Tool volume	m^3

Oven environment

Parameter	Definition	Units
m_a	Air mass	Kg
p_a	Air density	Kg/m^3
$c_{p,a}$	Air specific heat capacity	J/Kg.K
V_a	Oven volume	m^3

In the following sections the affixes a, r, f, t, p and o will be used for air, resin, fibres, tool, composite part and oven respectively.

A3: Equations formulation:

The power required to heat a mass from temperature T_1 to temperature T_2 is given by the following equation:

$Q = mc_p\Delta T = mc_p(T_2 - T_1)$ (1)

In the above equation the following parameters are defined:

Parameter	Definition	Units
Q	Heat flow or power	J
T	Temperature	K
m	Mass	Kg
c_p	Specific heat capacity	J/Kg.K

Equation (1) is applied to the air inside the oven, the tool and the composite part. Analytic derivations for the three materials are given below.

A3.1: Air inside the oven

The air mass inside the oven will depend on temperature and pressure:

$m_a = p_a V_A = \frac{P_A}{RT_A} V_A$ (2)

In the above equation, R is the universal gas constant (287 J/Kg.K). The oven pressure is kept constant at 1 bar (101253 Kg/m.s^2). The oven volume is taken to be 1m^3.

Substituting all the values to equation (2) for the air mass calculation results in the dependence of the air mass to the autoclave temperature (in degrees Celsius):

$m_a = \frac{101253}{287(273.15+T_A)} 1 = \frac{353}{273.15+T_A}$ (3)

In order to simplify the calculation of mass over a temperature range, an average mass is calculated based on the formula of equation (3):

$$\overline{m_a}(T_{A,2} - T_{A,1}) = \int_{T_{A,1}}^{T_{A,2}} \frac{353}{273.15+T_A} dT_A \Leftrightarrow \overline{m_a} = \frac{353}{T_{A,2}-T_{A,1}} ln \frac{273.15+T_{A,2}}{273.15+T_{A,1}}$$

The air heat capacity is 725 J/Kg.K. The energy for heating the air to the cure temperature will be:

$$Q_a = \overline{m_a} c_{p,a} \Delta T_A = \frac{353}{T_{A,2}-T_{A,1}} ln \frac{273.15+T_{A,2}}{273.15+T_{A,1}} * 725 * (T_{A,2} - T_{A,1}) = 255727 ln \frac{273.15+T_{A,2}}{273.15+T_{A,1}} \quad (4)$$

In equation (4), temperature is in degrees Celsius.

A3.2: Tool

The energy required to heat the tool will be:

$Q_t = m_t c_{p,t} \Delta T_A$(5)

For the cordierite material used in the tests, the specific heat capacity is ~40 J/Kg.K. The tool mass was 8 Kg:

$Q_t = 8 * 40(T_{A,2} - T_{A,1}) = 320(T_{A,2} - T_{A,1})$ (6)

A3.3: Composite part

The composite material is comprised by the resin matrix and the fibres. The masses of the resin and fibres are given as follows:

$m_r = p_r V_r = p_r V_p (1 - vf)$ (7)

$m_f = p_f V_f = p_f V_p vf$ (8)

The corresponding energy required to heat the composite will be:

$$Q_p = (m_r c_{p,r} + m_f c_{p,f}) \Delta T_A = (p_r (1 - vf) c_{p,r} + p_f vf c_{p,f}) V_p (T_{A,2} - T_{A,1}) \quad (9)$$

For the present exercise, the following values are used:

Material	Density (Kg/m^3)	Specific heat capacity (J/Kg.K)
Resin	1240	2000
Fibres	1800	1100
Fibres volume fraction = 60%		
Part volume = 2x10^{-4} m^3		

Plugging the above values to equation (9) results in the following:

$$Q_p = (1240 * (1 - 0.6) * 2000 + 1800 * 0.6 * 1100) * 0.0002(T_{A,2} - T_{A,1}) = 436(T_{A,2} - T_{A,1}) \quad (10)$$

A3.4: Summary of equations

The equations used for the energy calculations, as analysed above, are summarised in the table below.

	Equation
Air inside the oven	$Q_a = 255727 ln \frac{273.15 + T_{A,2}}{273.15 + T_{A,1}}$
Tool	$Q_t = 320(T_{A,2} - T_{A,1})$
Composite part	$Q_p = 436(T_{A,2} - T_{A,1})$