DE GRUYTER Sci Eng Compos Mater 2020; 27:325–334

Research Article

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Novel multi-zone self-heated composites tool for out-of-autoclave aerospace components manufacturing

https://doi.org/10.1515/secm-2020-0033
Received May 13, 2020; accepted Aug 13, 2020

Abstract: In this paper, a multi-zone self-heating composite tool is developed to manufacture out-of-autoclave complex and high-quality business jet lower wing stiffened composite panel. Autoclave manufacturing is regarded as a benchmark for manufacturing aerospace-grade composite parts. However, high accruing operational costs limit production rates thereby not being practical for smaller-scale companies. Therefore, significant work towards developing out-of-autoclave manufacturing is underway. In this study, a production line tool is developed with embedded heating fabric that controls temperature at the desired zones, replacing the need for autoclave cure. It investigates and identifies the optimal design parameters of the self-heating setup namely the placement of the heating fabric, zones, thermal management system, temperature distribution, heating rate and thermal performance using a thermal FEA model. The associated thermal characterisation of the tooling material and the part are measured for accurate simulation results. The design developed in this study will be used as production guideline for the actual tool.

Keywords: composites; heat transfer; thermal performance; self-heated; multi-zone

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1 Introduction

Advanced composite materials are widely used in many industries, including the aerospace and automotive sectors. The reason behind their increasing popularity is due to their high stiffness and strength to weight ratio, and the ability to tailor their structural configurations to meet high specific strength and stiffness [1]. These benefits are exploited in the aerospace industry by the replacement of more conventional materials like aluminium and titanium alloys with composites, in not only heavily stressed and critical primary structures such as the main wing and fuselage, but also in relatively small, lightly loaded components and sections of the structure, such as ailerons and fairings [2]. For instance, carbon fibre reinforced polymer (CFRP) forms a staggering 52% of Airbus's A350 XWB by weight [3]. As the demand for thermoset composites increases in number, size and complexity; the need for improved manufacturing techniques is vital. However, composites manufacturing is still a complex process that differs from alloys due to uncertainties inherited from their multi-phase compositing nature [4–6].

One of the benchmark manufacturing techniques that ensures high-quality composite components is the autoclave cure process. This process consolidates individual prepreg plies together via pressure and heat to initiate and complete the curing reaction for thermoset-based prepregs [7–9]. However, high costs for acquisition, operation, and tooling is required to set up the autoclave process. Additionally, this process is relatively inflexible, in which potential part designs are constrained by the autoclave size and restricted processing schedules. Hence, large autoclaves are often used inefficiently for small parts, where unnecessary excess energy is used in pressurising and heating [10]. As a result, the use of autoclaves is not sustainable and limits the possibilities to expand composites growth [7]. Therefore, to speed up manufacturing time and reduce costs without sacrificing quality, the businesses are keen to industrialise out-of-autoclave processes.

To overcome autoclave process challenges, alternative manufacturing technologies that aim to produce cost-effective aerospace-grade composites within shorter processing time are developing rapidly, such as resin transfer moulding (RTM), resin film infusion (RFI), and vacuum-assisted resin infusion (VARI) [8, 11]. These methods can provide good quality, large parts components if the temperature is controlled effectively. Temperature control is of particular importance, as it is a critical element of the resin curing management, resin gel time control, resin viscosity control, and material selection [12]. However, since ovens are used to elevate the temperature while curing, these methods still use a significant amount of energy and are limited by the size of the ovens used.

To reduce costs associated with autoclave and oven cure, researchers have been looking at exploiting the electrical conductivity of composite carbon fibre reinforcement. For instance, Dimoka *et al.* [13] utilised Joule's first-law using the carbon fibre as a conductor that generates heat when an electric current passes through it. Thermocouples and thermal cameras were used to confirm the temperature field uniformity, and their developed mould produced parts with good dimensional stability, while the maximum temperature was approximately 120°C. Yet, slight discrepancies between numerical and experimental simulations were observed.

On the other hand, comprehensive studies by Ramakrishnan, Zhu and Pitchumani [14, 15] used embedded carbon mats as internal resistive heating elements within the composite part to accelerate the curing process. The study focused on identifying the effects of parameters such as the number of mats and the power input on the quality of glass fibre, flat part. In Ramakrishnan *et al.* study [14], it was revealed that use of a single carbon mat with a high-power input led to the shortest cure time, but also corresponded to excessive internal temperature gradients during the process and a large void content in the composite product. Hence, it was concluded that for their setup, embedding two internal heating elements with a high-power input was determined to be optimal.

Alternatively, a recent study by Garmendia *et al.* [16] proposed a direct resistive heating method for curing on-site patch repairs. The study offered a complete simulation tool able to assess different configurations, current intensities, materials, etc. The study compared test results with the predicted values and reported good agreement between the two.

Another study by Athanasopoulos *et al.* [17] used lightweight sandwich structured moulds of carbon fibre reinforced plastic (CFRP) skins without any external heating element. Instead, the carbon fibre reinforcements of the mould's CFRP skin was used as heating elements, reaching up to 130°C maximum operating temperature. The study showed that the heated area of the mould in all the cases concludes with a thermal gradient at the edges. This leads to the necessity of determining the active region in which the temperature distribution remains almost uniform. The study concluded that the level of curing of the CFRP product manufactured with the method is similar to the level of curing of the respective conventional method.

In contrast, Hayes *et al.* [18] directly cured the resin by application of an electric current into the part rather than the tool, creating a large number of heating elements throughout the composite structure. These heating elements locally heat the surrounding resin of a 60×25cm part. The degree of cure is compared to conventionally cured composites using differential scanning calorimetry (DSC); additionally, three-point bend testing was used to determine the flexural strength and modulus of the composite samples. The results showed that a comparable level of cure could be obtained using the direct application of an electrical current as that of autoclave and oven cure processes.

The state-of-the-art literature presents the possibility of using a single self-heating zone to produce typical composite parts, limited in size, complexity and maximum heating temperature, mainly intended for research purposes. However, the developed tool is equipped with innovative multi-zone self-heating elements that efficiently and effectively control resin curing temperature, allowing the manufacturing of high-quality parts, with minimal energy consumption via a thermal management system designed for this purpose. Additionally, this tool is intended to manufacture a complex aerospace-grade composite part with the ability to reach high heating temperatures, while exploiting possibilities of reducing accruing operating costs compared with autoclave and oven cure systems as can be seen in Figure 1. The developed tool will be manufactured as part of a larger project to produce composite tooling business jet lower wing stiffened panels (COMBUSS Project [19]).

The design parameters of the self-heating setup, including the placement of the heating fabric, thermal management system, zones, temperature distribution, heating rate and thermal performance are investigated and verified using a thermal FEA model. The associated thermal characterisation of the tooling material and the part are measured for accurate simulation results. The design developed in this study form the production guideline for the actual tool.

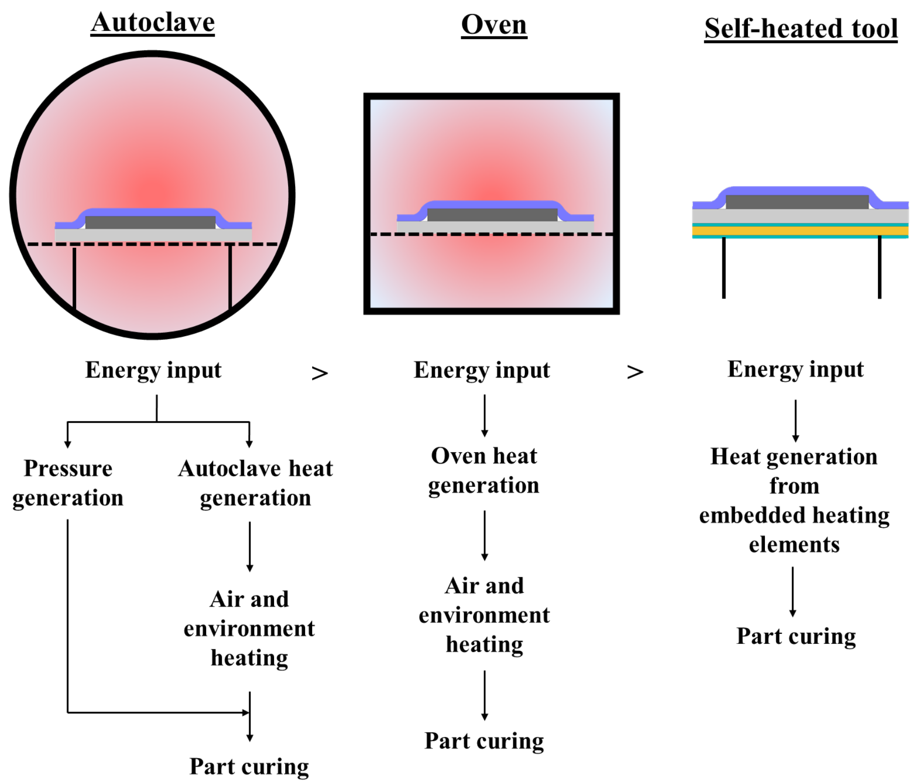

Figure 1: An illustration of the energy required to cure composite parts using various manufacturing techniques.

2 Tool development methodology

The multi-zone self-heated tool is intended to manufacture high quality stiffened lower wing panel parts. The part consists of a semi-flat panel, stiffened with eight T-bar stringers. Part bottom section rests on the tool. On the other hand, stringers are formed between caul sections. These sections are held in place during the curing process by a vacuum bag that is sealed on the tool. The above details are illustrated in Figure 3. The integration and configuration of the heating elements, materials of both the tool and part, and the thermal management system are explained in the following sections:

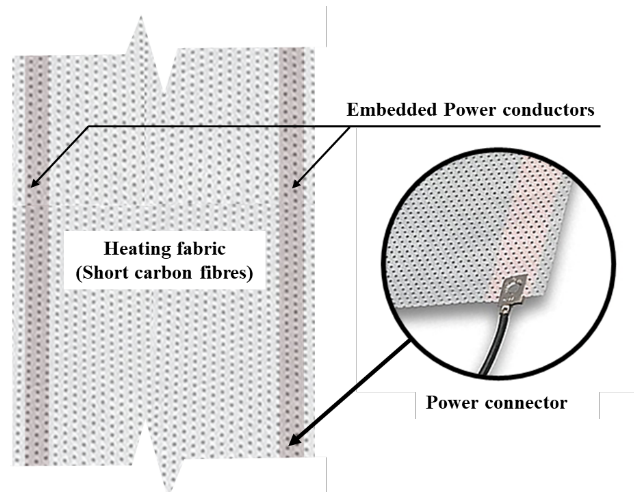

Figure 2: A section of LaminaHeat fabric embedded in the tool.

2.1 Heating elements

Since the developed tool is intended for production line, it is necessary to ensure that the integrated heating elements are: 1) well-distributed, covering the full surface rather than concentrating heat at limited region(s), 2) fully integrated with the tool material, so that they do not degrade the tool's strength after frequent heating cycles, 3) safe and easy to operate and maintain. To satisfy these requirements, PowerFabric^{TM} by LaminaHeat [20] shown in Figure 2 is used as heating elements to generate the required heat. The use of PowerFabric allows even heat distribution at proximity to tool surfaces. Also, being thin, the light laminate shape enables a high level of mechanical bonding following the tool shape with little maintenance

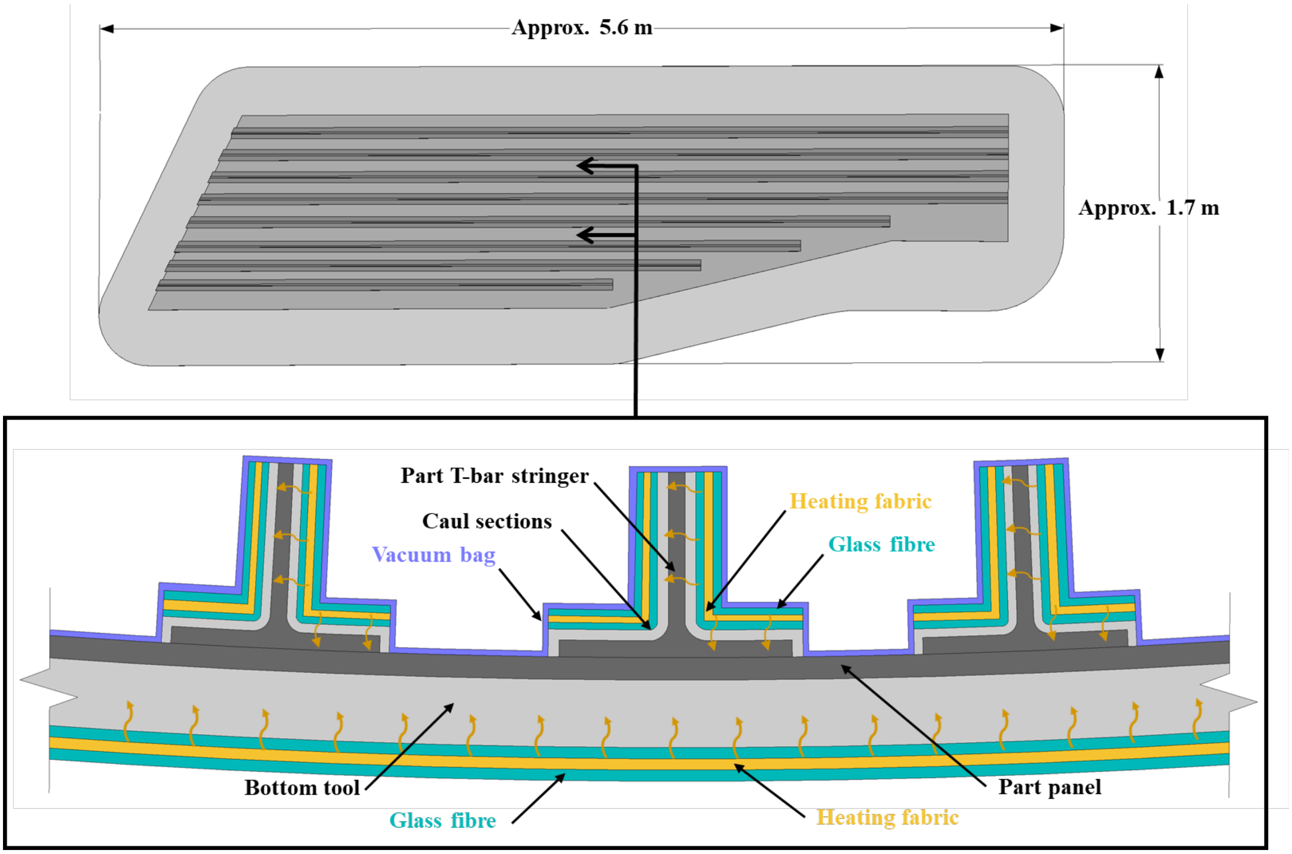

Figure 3: An illustration of heating fabric integration with the bottom tool and stringers.

required. Furthermore, it can operate in a wide range of voltages while being 99.7% heat efficient.

For the integration of the heating fabric, as the parts and the material of the tool use conductive carbon fibre reinforced polymer (CFRP) as presented in section 2.3, there is a need to di-electrically insulate heating fabric. This is achieved using 300gsm glass-fibre fabric on each side of the heating fabric. Therefore, the heating fabric will not be in direct contact with any carbon plies (neither part nor tool). The proposed position of the heating fabric will be on the backside of the bottom tool. This helps to integrate the heating fabric following tool manufacturing. On the other hand, the same approach is used to integrate the heating fabric to the outer sides of the caul sections that form stringers, see Figure 3.

2.2 Heating zones

To achieve a homogenised curing heat equivalent to the autoclave manufacturing process, there is a need to ensure that the embedded heating fabric is well distributed and controlled. Therefore, twenty heating zones are proposed; eight of which are integrated with the stringers longitudinally. However, in the bottom tool heating fabric will be placed latitudinally (see Figure 4), since the bottom tool is supported on structural stringers, forming bays that do not allow running the heating fabric in the long direction (as will follow in section 3.2.1 and Figure 9). It was concluded that placing heating fabric between the support structure bays will allow easier access if maintenance was required, compared to embedding them above the structural supports. As for the power supply, it is provided and controlled for each zone individually.

2.3 Tool structure

Following the operator's requirements for reliability, robustness and durability, the tool is designed with an epoxy-based tooling prepreg CFRP plies. Additionally, piles of glass prepreg are used to di-electrically insulate the heating fabric. The plybook for both the bottom tool and stringer's cauls is presented in Table 1.

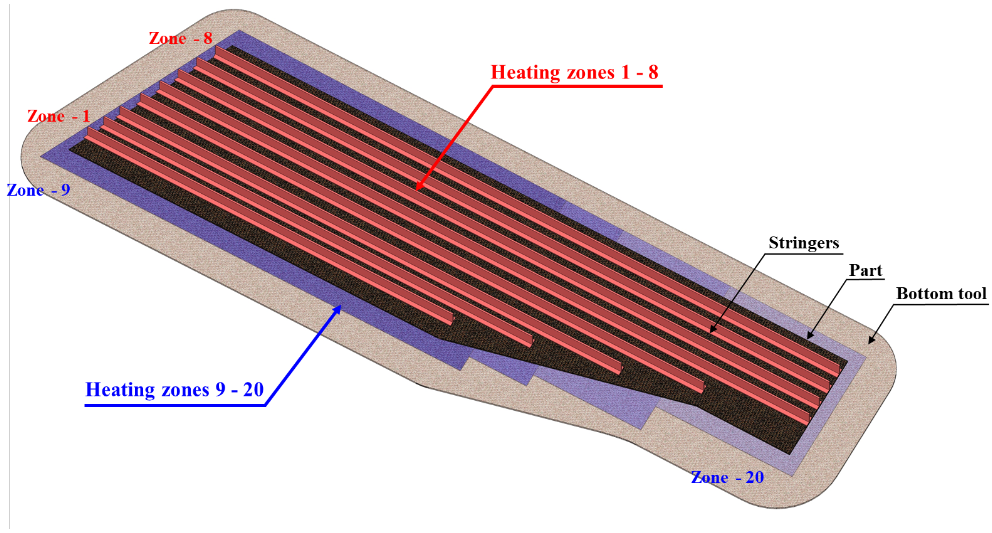

Figure 4: An illustration of the self-heating zones.

Table 1: Plybook for the developed self-heating tool.

Ply ID	Material	Thickness
Bottom tool		
1-2	Carbon fibre	0.2 mm
3-15	Carbon fibre	0.6 mm
16	Glass fibre (insulator)	0.6 mm
17	Heating fabric (PowerFabric)	0.3 mm
18	Glass fibre (insulator)	0.6 mm
Caul plate		
Ply ID	**Material**	**Thickness**
1	Carbon fibre	0.2 mm
2-6	Carbon fibre	0.6 mm
7	Glass fibre (insulator)	0.6 mm
8	Heating fabric (PowerFabric)	0.3 mm
9	Glass fibre (insulator)	0.6 mm

2.4 Thermal management system

A robust thermal management system is important for processing of the large integrated structures with significant variations in temperature field of the curing part and for eliminating fluctuations of the final part properties across the cured part. The thermal management system aims to efficiently control the thermal cure of the resin, as shown in Figure 5. The system is designed with the capability to control the temperature of each zone shown in Figure 4 individually.

The processing temperature window required for the used resin system is between 160°C–180°C as shown in Figure 5. This resin system is a degassed, mono-component resin made specifically for resin transfer moulding processes, and mainly in the aerospace sector. Once cured, the resin can be used in a wide temperature window spanning −60°C to 180°C.

To precisely control the curing process, the thermal management system consists of the controller unit, which comprises of the proportional–integral–derivative (PID) temperature controllers, temperature data acquisition hardware and the power electronics unit containing the power electronics hardware. The power electronics unit is responsible for powering the heating element lines according to the controller unit commands. Additionally, there is the Graphical User Interface (GUI) for communication to the controller unit, which estimates the temperature gradient in space and time to regulate the PID parameters of the energy supplied to the zones. The additional functionality of the GUI also enables to monitor every aspect of the manufacturing process based on the tool temperature, degree of cure and resin viscosity which would enable the tool to operate with any fibre and resin system. The elements of this thermal management system are shown in Figure 6.

The feedback from the thermocouples is an essential element that feeds into the thermal management loop. Thus, it is proposed that 1-3 thermocouples are placed on the bottom part corresponding to each heating zone; on the other hand, 1-4 are to be placed on each stringer. The total expected number of thermocouples is 32, following the capacity of the proposed PIDs. Although the in-plane position of the thermocouples is not yet identified in this study, it's important to note that the thermocouples will be embedded under the surface ply of the tool and connected

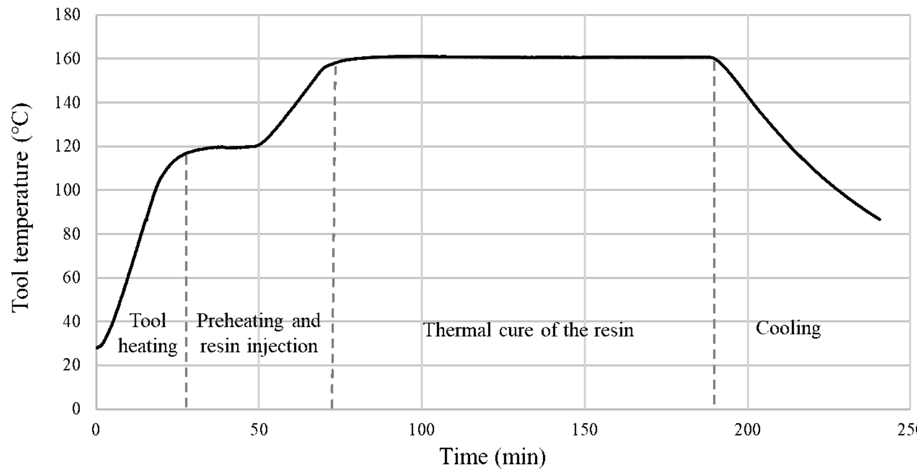

Figure 5: Resin cure curve.

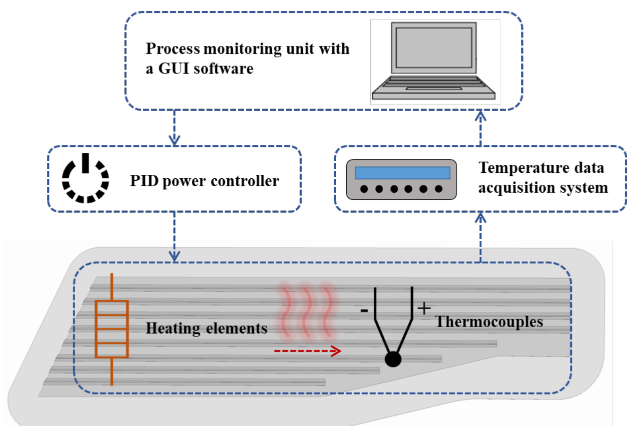

Figure 6: Overall system description of the thermal management system.

using nanowires; this surface proximity will provide accurate part temperature readings.

3 Results and discussion

3.1 Material characterisation

To conduct the thermal simulation and the heat transfer from the heating fabric to the part, three thermal properties were estimated as presented in the following sections.

3.1.1 Thermal conductivity

Thermal conductivity is tested for the cured tool materials (Carbon fibre and glass fibre prepregs), and on the actual part material, using LaserComp FOX 50 apparatus in accordance with ISO 8301/ASTM C518. First of all, a calibration run was performed and was within 3% of the book values between 50°C-100°C. The top plate was then set to 90°C, and the lower plate to 70°C for a mean temperature of 80°C. After achieving equilibrium, results were recorded. Later, a thicker sample was added to reduce the surface resistance errors, while using Peltier cooling and heating to maintain plates' temperature within <0.1°C of the set temperatures. The obtained results are presented in Table 2.

Table 2: Thermal conductivity and specific heat results for the tooling prepreg and the part material.

Material	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) at 80°C	Specific heat ($MegaJ/m^3K$)	
		44°C to 72°C (Average of 58°C)	72°C to 100°C (Average of 86°C)
Carbon fibre (tool)	0.622	2.030	2.361
Glass fibre (insulator)	0.542	2.566	2.791
Resin and reinforcement (part)	0.304	2.931	3.256

3.1.2 Specific heat

The Specific heat (Cp) for all three materials was estimated using the same apparatus used to calculate thermal conductivity earlier, *i.e.* LaserComp FOX 50 in accordance with ASTM C1784 standards. Apparatus's isothermal plates were both run at 44°C for a few hours, followed by 72°C for the same time, followed by an increase to 100°C. Recorded results were used to calculate Cp by LaserComp software, which are presented in Table 2.

3.1.3 Coefficient of thermal expansion

Three 6×6×6 cubic mm samples of the chosen tooling prepreg Carbon fibre used in manufacturing the tool were tested to estimate the coefficient of thermal expansion (CTE) as shown in Figure 7. The test was conducted in accordance with ISO 11359-1 and 2, for temperatures between 10°C and 190°C. The average CTE values between 23°C – 140°C, and 23°C – 180°C were 63×10^{-6} K^{-1} and 70×10^{-6} K^{-1}, respectively.

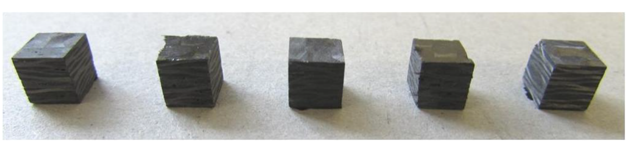

Figure 7: Coupon cut for the CTE testing cubes.

3.2 Heating strategy and process verification

Given the fact that the embedded heating fabric is used to heat the setup, the main challenge is the adequacy of the heat provided to reach the desired temperature and its rate. Additionally, due to the limitations associated with the tool structure (egg crate), a gap between the heating elements also presents a concern. Therefore, in this section, the above two aspects are simulated to verify the compatibility of the tools. The simulations are conducted using the commercial PAM-RTM FEA software, a module of PAM-COMPOSITES [21]. The system is initially modelled with 2D shell Tria elements to obtain the initial results, including the heating time. Then the model is further developed to 3D solid Tetra elements for further calculations such as the through thickness temperature gradient.

3.2.1 Heat transfer considering the egg crate structure

The composite tool is supported by a metal frame to ensure stability and mobility. As a result, structural stringers running latitudinally are required to fix the composite bottom tool to the frame. This creates egg crate structures separated by 8 mm intervals between spans used to place the heating fabric as can be seen in Figure 9.

To ensure that this gap will not present cold spots that affect the resin cure, the tool is modelled with 4,062,660 elements, with an average mesh size of 15 mm with smaller mesh in the 8 mm gap areas. The laminate builder included in the PAMRTM generates the laminate plies where the material properties (for fibre and resin), individual fibre orientation, the fibre content and ply thickness can be defined on a ply level, as described in Figure 8. The ply

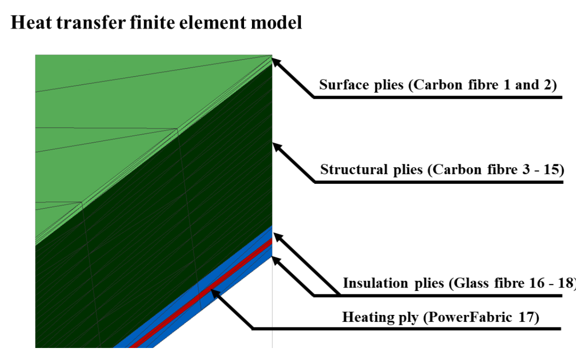

Figure 8: Modelling of laminate plies in heat transfer simulation.

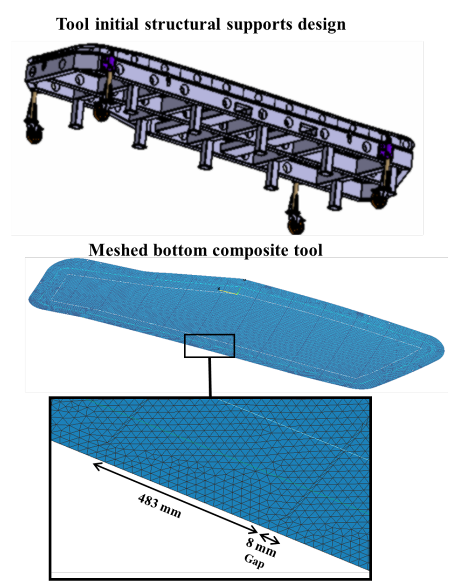

Figure 9: An illustration of the gap between the heating elements due to structural supports.

thickness ranges from 0.6mm for the bulkply to 0.2mm for the surface ply based on the plybook in Table 1.

In order to identify the ideal mesh size, a mesh convergence study was performed, ranging from 10mm to 35mm. Based on the initial analysis, it was concluded that a mesh size range from 10 to 25mm gives almost similar temperature gradient along the thickness and also along the ply fibre direction of the laminate.

The process duration is set at 15,000 seconds to cover the maximum heating time, with a time step of 10 seconds for accuracy. The exact boundary conditions are applied based on the zones set in Figure 4, with separate heating zones controlled individually in the model, to represent the actual tool along with the thermal management system.

Simulation results obtained and presented in Figure 10 show the initial heat transfer from the tool to the part, at the start of the resin injection stage (from 120°C) following the rates shown in Figure 5. The presence of the 8 mm gap can be seen as colder zones up to the 8^{th} minute; after which, the temperature distributes evenly, and gap presence dissipates by the 12^{th} minute of heating as can be

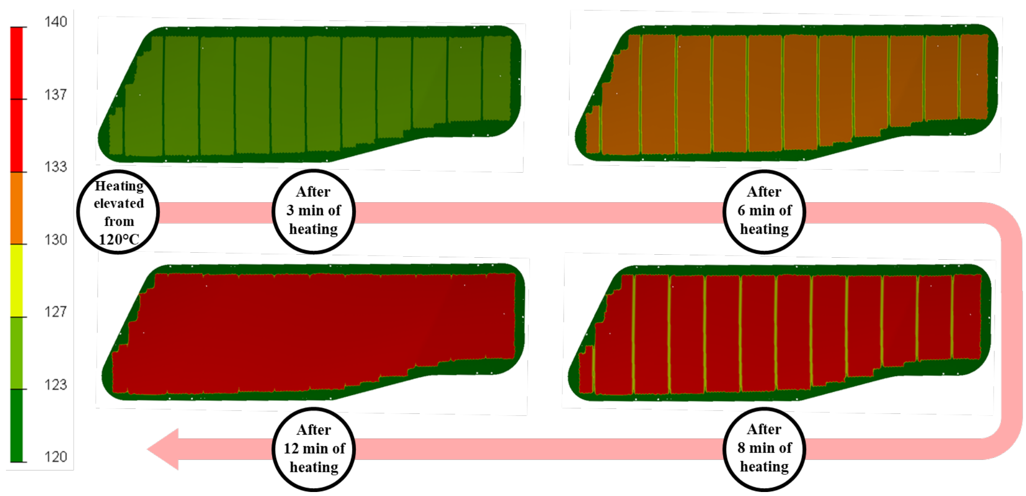

Figure 10: Preheating stages for the composite tool before resin injection.

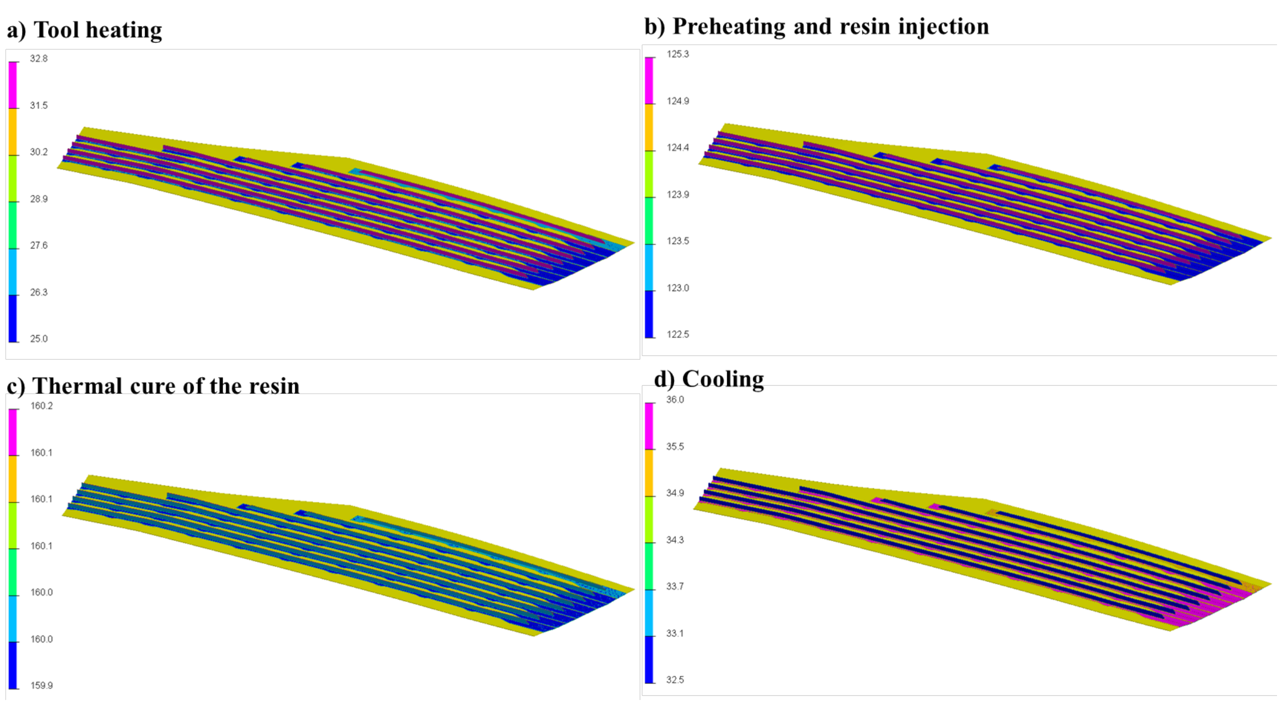

Figure 11: Thermal transfer simulations of all curing stages.

seen in Figure 10. This verifies that the gap of 8 mm on the egg crate structure is acceptable and will not influence the curing process significantly, as it dissipates around 140°C before reaching the required cure temperature of 160°C.

3.2.2 Resin cure curve simulation

The heat transfer simulation is done on the part to make sure an ideal heat transfer can be achieved throughout the part with the current setup. The key objective during the process is to ensure that the heating elements are capable of delivering the required temperature-time curve shown in Figure 5 to the part.

Since stringers' heating zones overlap with bottom tool zones, it is important to ensure that heating is applied in such a way that no excessive hot spots occur in these areas. Thus, heat transfer simulations play an important role in optimising the power supply to the heating elements to ensure 1) the temperature-time curve is followed, 2) a uniform heat distribution across the part including the stringers is maintained. This can be achieved by further work following tool fabrication using an optimisation tool, that aims to select the optimum heating parameters to reduce the difference between the planned cure curve and the actual temperature reading across the part. Heating parameters can be represented by the power supplied to each heating zone, while the objective function will be derived from the feedback of the thermocouples.

It was concluded that there is a need to apply lower temperature to stringers' heating zones (below the required cure curve at a specific time) compared with the bottom tool. This reduces the possibilities to have hot spots in overlapped heating zones. Implementation of this heating strategy to all resin cure stages is shown in Figure 11. Although reasonably uniform temperature is achieved across the entire part, there is a need to further optimise heating management parameters on the tool using the feed obtained from the thermocouples rather that the FEA simulation.

4 Conclusions

In this study, a multi-zone self-heating composite manufacturing tool is developed to manufacture high quality stiffened lower wing panel parts. The key findings and conclusions are:

- The proposed embedded heating elements solution distributes heat evenly, at proximity to tool surfaces, while providing a high level of mechanical bonding with the tool.
- Twenty individual zones controlled by a thermal management system is proposed, based on the configuration of the tool elements and support structure constraints.
- The thermal properties of the tool, insulator and the part material are tested to ensure compliance and provide accurate input for the simulations.
- The heat transfer simulations conducted using FEA software verified that the tool configuration and the heating elements selected provide sufficient uniform heat required to achieve the desired resin cure.

The developed tool is being fabricated based on the study findings and conclusions. Nevertheless, future work will focus on optimising tooling parameters such as the thermal transfer and thermocouples positions, and on conducting further testing to verify and calibrate the system to obtain an optimum degree of resin cure for parts manufactured using the tool.

Acknowledgement: The authors gratefully acknowledge the contributions from OFFICINE MECCANICHE IRPINE SRL - OMI (IT) and TWI Ltd (UK). This paper is part of COMBUSS project [19], which has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No 821297. https://www.combuss.eu/

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