Numerical Studies of Integrally-Heated Composite Tooling

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Abstract:

Integrally-heated tooling is one of the technologies available for 'out-of-autoclave' processing of advanced thermoset polymer composites. However, there have been relatively few studies of optimization; design and manufacture of tooling often lacks a methodology, and may result in poor heat distribution and low thermal efficiency. In the current study, several combinations of design parameters (flow channel cross-section, topology and channel spacing) have been investigated, using a design of experiments approach, and evaluated through CFD numerical simulation to investigate heating time and mould surface temperature variation. Signal-to-Noise ratio and ANOVA have been used to identify an optimal design configuration. Results suggest that the layout of the channel and its separation play a vital role in the thermal performance of the integrally-heated tool, and that the channel profile has a negligible effect.

1. Introduction

Cost reduction and improved energy efficiency in composite manufacture require alternatives to process CFRP by autoclave using prepregs [1-4], as well as produce large composite products as a single piece [5]. Amongst other technologies, there has been a recent focus on integrally-heated tools, which have been applied to a variety of processing technologies, including compression and resin transfer moulding (RTM) [6, 7]. Heating by circulation of a heat transfer fluid offers a number of advantages over ovens or autoclaves [8, 9] and different studies been carried out in the development and improvement of this concept [10-12]. However, much of the previous research has concentrated on tooling for thermoplastic processes [13-18], and there has been relatively little systematic work on thermosetting-matrix composites. This research focusses on the effect of three design factors in water-circulated integrally heated tools. The test cases are designed using Taguchi's orthogonal array (OA) method [19-23]. Numerical simulation of transient heat transfer has been carried out for each of the proposed designs of an integrally-heated tool. The statistical approach of signal to noise (S/N) ratio as well as analysis of variance (ANOVA) has been applied to allow the interpretation of the numerical results and to identify the optimal parametric combination [24-26].

2. Overview of Integrally-Heated Tool:

2.1 Basic Principle

In the current study three parameters are described as design factors: channel geometry, channel layout and channel separation. The factors are expected to be significant in obtaining optimum design of an integrally-heated tool that can achieve the most uniform temperature in the minimum heating time. The desired surface temperature will be the curing temperature of a typical low temperature moulding (LTM) prepreg [27, 28]. Each tool model consists of five components, including metal and composites as shown in Fig. 1, with the heating channel embedded in the mould under the tool face. Table 1 lists the main thermal and mechanical properties of the materials used. These properties have been derived from literature sources and rules of mixture, and will be subjected to measurement and validation in future studies.

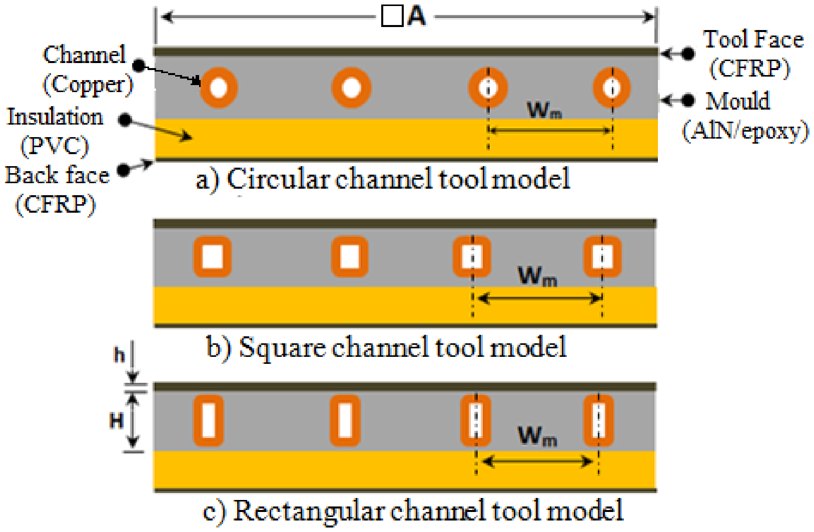


Figure 1. Schematic architecture of the experimental test tool models [4, 29-37].

Properties		**Unites**	**Materials**					
			Water @ 90°C	**Copper**	**PVC Foam**	**CFRP** 0°/90°		**AlN/epoxy**
Thermal	V_f	%	-	-	-	50		68.5
	μ	$Kg/m.s$	3.1×10^{-4}	-	-	-		-
	k	$W/m.K$	0.677	401	0.04	4.09 In-plane	0.64 Through-plane	7
	α	m^2/s	1.7×10^{-7}	1166×10^{-7}	1.6×10^{-7}	23.8×10^{-7}	3.7×10^{-7}	41×10^{-7}
	ρ	kg/m^3	964.95	8933	160	1600		1956
	c_p	$J/kg.K$	4201.5	385	1600	1075.5		875
Mechanical	σ_{max}	MPa	-	455	5.1	600		320
	τ_{max}	MPa	-	230	2.6	90		61.4
	E	GPa	-	117	0.17	70		7.89
	G	GPa	-	44	0.066	5		2.93
	υ	-	-	0.3	0.3	0.1		0.24

Table 1. Properties of the proposed tool model materials.

2.2 Limitations of current tool

Some basic structural constraints were imposed on the proposed tool models. For example, providing sufficient tool strength while reducing thermal resistance led to the conclusion that in Fig.2, $H \geq 16$mm and any $h \geq 0.5$mm. This situation could be relevant to RTM, where dry reinforcement is clamped within the mould.

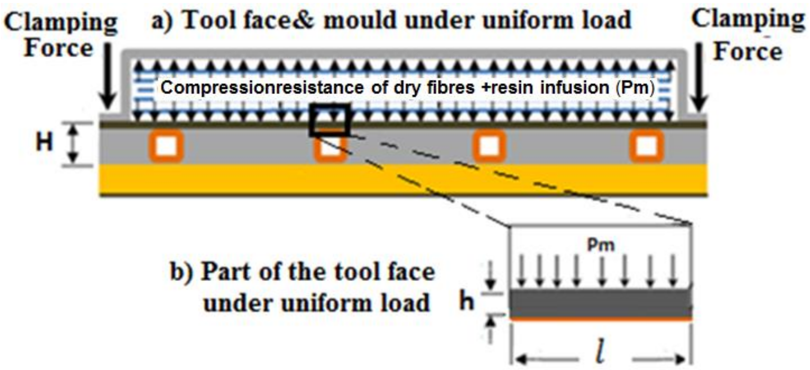


Figure 2. Section of the proposed tool model as used in RTM, with compression of reinforcement.

The pressure drop of a fluid flowing in a channel is a function of channel length, hydraulic diameter and fluid mass flow rate [29]. Channel length and diameter are designed accordingly [38] to ensure that the total pressure drop does not exceed the available pump pressure.

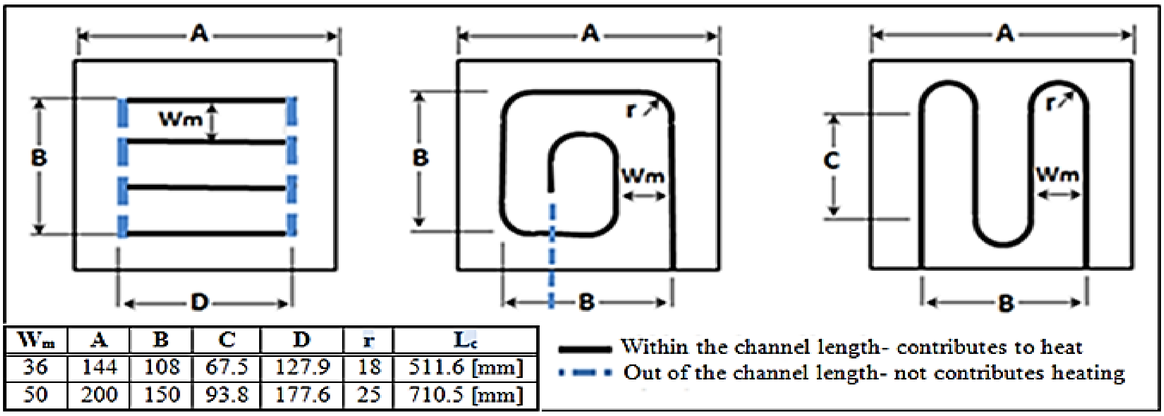
3. Design of Experiments

Nine test cases are considered according to Taguchi's orthogonal array L9. Table 2 explains the arrangement of the variables and their levels, where each test case represents a numerical experiment. Design of the tool model in each test case involves changing the levels of the selected variables of: channel layout (A), channel profile (B) and channel separation (C), while keeping other factors constant (Fig. 3). The first two parameters have three levels, but the last has only two levels.

Test Cases	**Parameters and Levels**			**Results**
	A	B	C	
1	Zigzag (Z)	circular (c)	1	x_1
2		square (s)	2	x_2
3		rectangular (r)	1	x_3
4	Helical (H)	circular (c)	2	x_4
5		square (s)	1	x_5
6		rectangular (r)	2	x_6
7	Parallel (P)	circular (c)	2	x_7
8		square (s)	1	x_8
9		rectangular (r)	1	x_9

Table 2. Design parameters and their levels during the test cases.

Calculation of the key dimensions of each tool model (Fig. 3) is based on the proposed value of channel separation. The channel profiles have equal cross section areas.



W_m	A	B	C	D	r	L_c
36	144	108	67.5	127.9	18	511.6 [mm]
50	200	150	93.8	177.6	25	710.5 [mm]

Figure 3. Geometries and dimensions of the proposed tool models; zigzag (right), helical (middle) and parallel (left).

4. Numerical Simulation

ANSYS-CFX software is used to model the thermal performance. The proposed flow rate must ensure turbulent flow (Re_D ≥10,000), which makes heating faster [10]. The flow rate in each branch of the parallel model is defined by the equation of continuity and head loss equality [39]. The heating medium will be water at 90°C, while the initial temperature of the tool parts and the ambient is assumed to be 25°C. A forced convection boundary was specified at the interface between the water and the channel. The running time step size of the current study is the smaller of the convection and thermal diffusion timescales.

From the numerical results, two characteristics (heating time per unit mass and surface temperature variation) are calculated as the response variables. The coolest heated point on the tool face is selected to interpolate and define the required heating time (H_t in Fig. 4), for heating up the total tool surface to a target temperature (T in Fig. 4, arbitrarily defined as 90% of the water temperature) – this temperature is used to compare the heating performances of the test cases. Then a ratio of heating time per unit mass is calculated for each case.

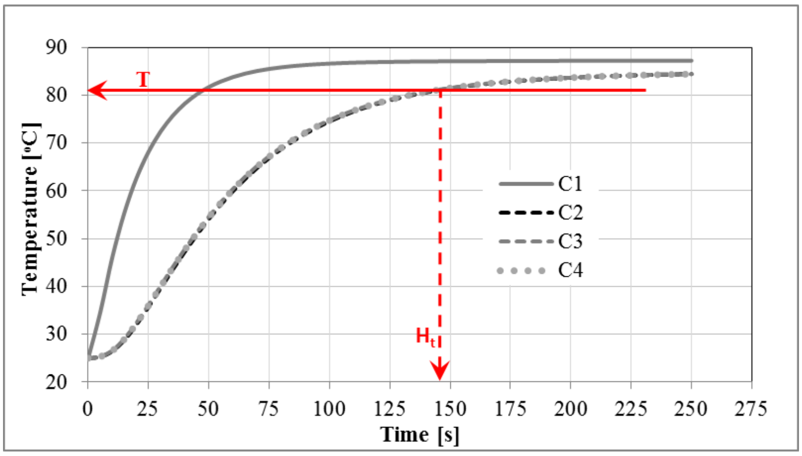


Figure 4. Heating curve of points at the surface corners of a tool model with helical layout, square channel and 36mm separation.

The second response variable is defined as the difference between the area-weighted average temperature of the tool surface and the target temperature. Fig. 5 illustrates temperature distributions over the surfaces of the simulated tool models in three test cases, after reaching time H_t.

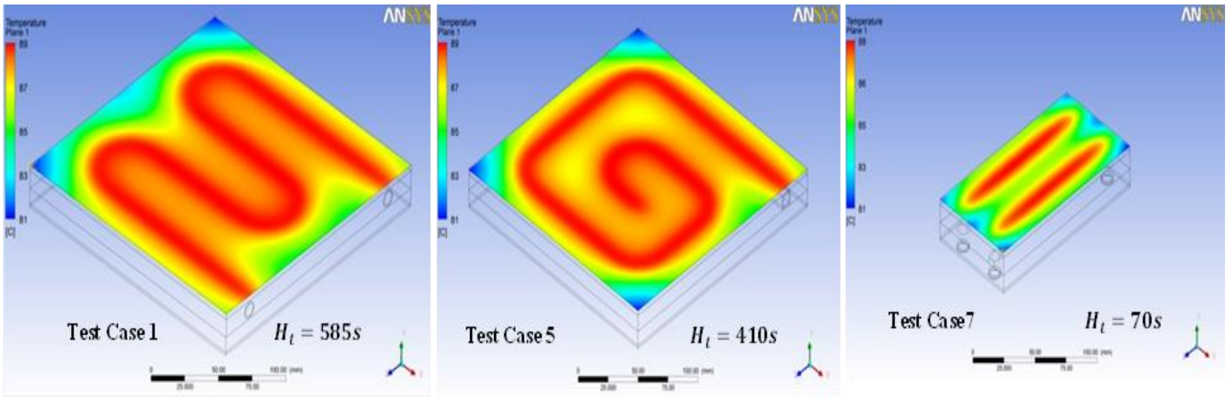


Figure 5. Surface temperature distribution of some test cases at the corresponding$(\boldsymbol{H_t})$.

5. Design Optimisation

The quality characteristic investigated in this study was considered as "lower-is-better" (LB). The S/N ratios, for an LB characteristic, can be calculated as follows [22]:

$$S/N_{LB} = -10\ Log\left(\frac{1}{q}\sum_{i=1}^{q} x_i^2\right) \tag{1}$$

Where x_i is value of the response variable or the simulation results, and q is number of repetitions. S/N results for heating time and temperature variation are shown in Fig. 6.

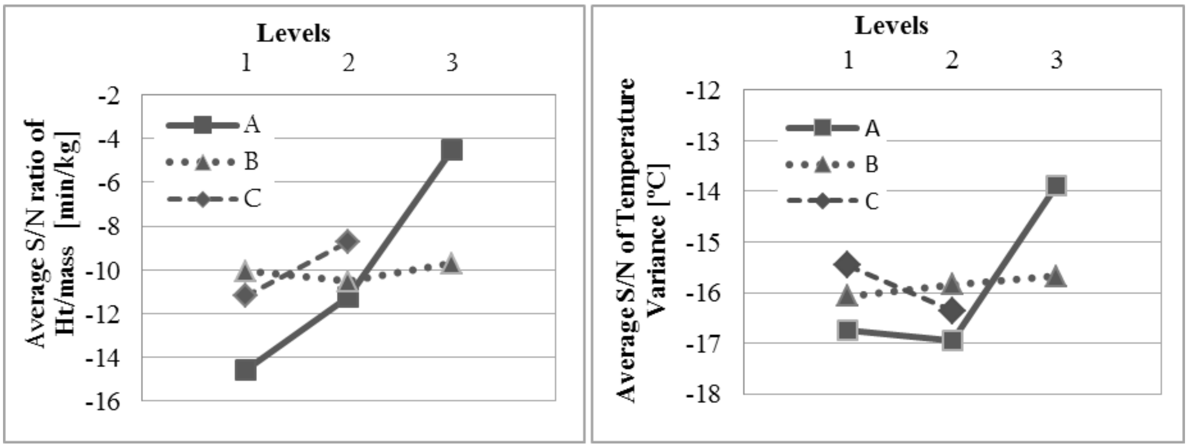


Figure 6. Main factor effects of average S/N ratio for heating time per unit mass (left) and temperature variance (right).

Results show that the channel profile has little effect on the heated tool performance, while the geometrical alignment (parameter A) has high effectiveness on the response variables – the parallel arrangement (level 3) is clearly preferred. Analysis of variance (ANOVA) is used to analyse the response variables, find the significant design parameters and predict optimal design parameters [26, 40]. The expected result of the combination of the optimal design parameters is predicted by the following expression:

$$\mathrm{y_{opt}} = \mathrm{f}_{A_{\mathrm{opt}}} + \mathrm{f}_{C_{\mathrm{opt}}} - \frac{1}{n}\sum_{i=1}^{n} y_i \tag{2}$$

Where $\mathbf{f}_A$ and $\mathbf{f}_C$ are the average performance (factor effect) for the parameters **A** and **C** respectively, $\boldsymbol{y}_i$ is the test results (the S/N ratio value of x_i). The 90% confidence interval is calculated and two different optimal conditions are achieved, for both response variables, which indicate that whenever the heating is faster the temperature variation will be higher.

6. Conclusion

Results have shown that the circular shape remains the most appropriate and economic channel profile since this factor has little effect on thermal efficiency. The channel layout and separation are the most crucial factor in achieving the optimal temperature uniformity and heating time over the surface of the tool. The parallel arrangement (P) is significantly better. Further investigation is required to determine the long-term performance of the integrally heated tool, while the numerical simulation results will need practical verification.

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