Materials and Design 64 (2014) 477–489

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Numerical simulation and design optimisation of an integrally-heated tool for composite manufacturing

Rzgar Abdalrahman [a], Stephen Grove [b,*], Adam Kyte [b], Md Jahir Rizvi [b]

[a] Mechanical Engineering Department, Polytechnic University of Slemani, Slemani, Kurdistan, Iraq
[b] School of Marine Science & Engineering, Plymouth University, Plymouth PL4 8AA, UK

ARTICLE INFO

Article history:
Received 29 April 2014
Accepted 10 July 2014
Available online 1 August 2014

Keywords:
Composite
Heated tool
Design of experiment
Numerical simulation
Optimisation

ABSTRACT

Tooling design is crucial for the production of cost-effective and durable composite products. As part of the current search for cost reduction, integrally-heated tooling is one of the technologies available for 'out-of-autoclave' processing of advanced thermoset polymer composites. Despite their advantages, integrally-heated tools can suffer from uneven distribution of temperature, variability in heat flow rate and inconsistency in heating/cooling time. This research, therefore, investigates a number of design variables such as shape and layout of heating channels in order to improve the thermal performance of an integrally-heated tool. Design of Experiments (DoE) has been carried out using Taguchi's Orthogonal Array (OA) method to set several combinations of design parameters. Each of these design combinations has been evaluated through numerical simulation to investigate heating time and mould surface temperature variation. The simulation results suggest that the layout of the channels and their separation play a vital role in the thermal performance. Signal-to-Noise (S/N) ratio and analysis of variance (ANOVA) have been applied to the results obtained to identify the optimal design combination of the integrally-heated tool. Statistical analysis reveals that the heating performance of an integrally-heated tool can be significantly improved when the channels' layout is parallel. The shape of the channels has negligible effect and the distance between the channels should be determined based on the production requirement.

1. Introduction

All types of fibre-reinforced composite products require accurate and robust tooling because the performance of the tool determines the integrity of the manufactured part. Tooling not only provides a reproducible geometry, it also provides consolidation which influences the mechanical and physical properties of the product and helps the transfer of heat into the polymer matrix. Throughout the last two decades, composite manufacturers have given high priority to cost reduction and increased energy efficiency in composite manufacturing [1]. In advanced composites, this requires alternatives to autoclave processing of prepregs [2–4]. Also the increasing demands of producing increasingly large composite products as a single piece cannot be fulfilled using traditional manufacturing methods as larger tools are required [5]. A variety of technologies known as 'Out of Autoclave' (OoA) processes includes novel approaches to heating of tooling, liquid composite moulding (e.g. resin infusion) and prepregs which can produce satisfactory fibre content without autoclave pressure [6–10].

In integrally-heated tools, the heating element and the tool are combined in-mould or on-mould [11]. This approach transfers the required heat through the mould and across its surface to cure the composite faster than traditional methods. A number of such heated tools are commercially available and are suitable for closed mould processes such as compression moulding, resin transfer mould (RTM) and its variations [12,13].

However, there have been few systematic studies of heated tooling for thermoset composites. This study has been carried out with the aim of improving the thermal performance of integrally water-heated composite tooling, suitable for a variety of liquid composite moulding or low temperature prepreg processes. Three design factors are selected and nine design combinations have been identified according to Taghuchi's orthogonal array. Numerical simulation of transient heat transfer has been carried out for each of the proposed nine designs of the integrally-heated tool. Then the statistical approach of S/N ratio has been applied to allow the control of the response variables and identify their optimal parametric combination. Analysis of variance has been applied to investigate the effect of design parameters on the response

* Corresponding author. Tel.: +44 1752 586124.
E-mail address: S.Grove@plymouth.ac.uk (S. Grove).

http://dx.doi.org/10.1016/j.matdes.2014.07.019
0261-3069/

Nomenclature

A	length of the square tool model
A_c	channel cross section area
A_s	wet peripheral convection area of the channel
A_i	values of the corresponding area weights
A	design parameter of channel layout
B	a dimension of the channel layout
B	design parameter of channel profile
b	internal length of the rectangular channel profile
C	a dimension of channel layout
C	design parameter of channel separation
C.I.	confidence interval
c_p	specific heat
c	internal width of the rectangular channel profile
D_i	internal diameter of the circular channel profile
D_h	hydraulic diameter of the channel profiles
D	a dimension of channel layout
E	modulus of elasticity
E_{CF}	modulus of elasticity of CF
F_P	variance ratio of each parameter
$F(1,\bar{f}_e)$	value of variance ratio at the DoFs of 1 and $\bar{f}_e$ from F-table
f_f	Moody, Darcy or Fanning friction factor
f_{P_j}	average performance (or factor effect) of each parameter at each given level
f_{max} and f_{min}	maximum and minimum average performance (factor effect) for each parameter
f_A and f_C	average performance (factor effect) for the parameters **A** and C respectively
f_T	total degrees of freedom of the test cases
f_P	degree of freedom of each parameter
f_e	degree of freedom of the error term
f_A, f_B and f_C	degree of freedom of the parameters A, B and C respectively
f_e	pure degree of freedom of the error term after pooling
H	height of the mould and the tool surface together
H_t	heating time
h	thickness of the tool surface
h_w	heat transfer coefficient between water and channel surface
h_t, h_b and h_s	heat transfer coefficients at the top, bottom and side surfaces respectively
i	test case counter
j	level counter
k	water thermal conductivity
L	ratio between the area and the perimeter of a given tool surface
L_c	constant channel length
L_s	thickness of the side surface
L_{hel}, L_{par} and L_{zig}	lengths of the helical, parallel and zigzag layout channels, respectively
l	internal length of the square channel profile
$\dot{m}$	mass flow rate
N_P	total number of the levels of each parameter
n	total number of the test cases in OA
P	peripheral wet perimeter of the channel
P_m	applied pressure on the mould surface
P_P	percentage contribution of each parameter
ΔP	pressure drop
ΔP_1, ΔP_2, ΔP_3 and ΔP_4	pressure drop of the parallel branches
Q_1, Q_2, Q_3 and Q_4	volumetric flow rate in the main inlet and the four parallel branches
Q_{in}	amount of heat entering the tool
Q_{loss}	amount of heat losses from the tool
Q_{st}	amount of heat stored in the tool
q	number of replication or repetition
R	ratio of channel length to the tool surface area
Re_D	Reynolds number according to the hydraulic diameter
r	radius of the channel bends
S_{P_j}	sum of the test results containing each parameter at each given level
SS_T	total sum of squared deviations of the test results
SS_P	sum of squared deviations of each parameter
SS_e	sum of squared deviations of the error term
SS_A, SS_B and SS_C	sum of squared deviation of the parameters A, B and C, respectively
T	temperature
T_m, T_∞	mould and ambient temperatures
T_t, T_{max} and T_{min}	the target and two temperatures higher and lower than the target temperature at any point
T_{ave}	area-weighted average temperature
T_i	values of the temperatures for which an average is being calculated
t	time
t_{max} and t_{min}	desired heating time for achieving t_{max} and t_{min} at a given point
u	fluid velocity
V_e	variance of the error term
V_P	variance (or mean of the squared deviations) of each process parameter
$\overline{V}_e$	pure variance of the error term after pooling
W_m	channel separation value
x_i	values of the response variable or the simulation results
x_{opt}	equivalent value of y_{opt}
y_i	test results (the S/N ratio value of x_i)
y_{P_j}	test results of each parameter at each given level
y_{opt}	expected result of the optimal combination according to S/N ratio
z	total number of the tests contains intended parameter at a given level
ρ	density of water
δ_{max}	maximum deflection
σ_{max}	maximum tensile strength
τ_{max}	maximum shear strength
μ	dynamic viscosity

strategies of heating time per unit mass and on the maximum temperature variation over the tool surface, to identify the most critical performance parameters.

2. Literature survey

Several tool heating technologies, for instance; electric heating, radiation and fluid circulation are being used in the integrally-heated tools [3], but the last technique is considered the most convenient. Also among different techniques of heated fluid circulation, such as; nanotube heating [14], surface generation [15] and tube circulation or conformal channel method [16], the last is considered to be the most appropriate – see Table 1 [11].

Studies have already been carried out for optimising the geometry of the mould and the channel as well as selecting the proper heating fluid and tool material [17]. The thermal response of an oil-heated tool and the influence of different fluid velocities have been investigated numerically by Ding et al. [18]. They deduced