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A methodology to reduce thermal gradients due to the exothermic reactions in composites processing

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Abstract

In resin transfer molding (RTM) process, a polymer composite part is fabricated by injecting a thermoset resin into a fiber preform placed in a closed mold cavity. After the infiltration of the resin into the empty spaces in the mold, the manufacturing process is characterized by a curing reaction, which is an exothermic resin polymerization phenomenon that cross-links the resin and results in a solid structure. In most cases, the resin cure is initiated by heating the mold. The heat released during the reaction can cause temperature gradients in the composite, which leads to residual stresses in the part. Residual stresses are undesirable as they can cause shrinkage and warpage. By controlling the temperature of the mold walls, one can control the cure reaction and reduce the thermal gradients through the composite part. In this paper, we present a methodology based on scaling analysis of the energy balance equation to manage the heat generated by the cure reaction that minimizes the temperature gradients before the resin solidifies. The method capability is demonstrated with a highly reactive polyester resin infiltrated into different types of glass fiber preforms in a rectangular mold.

Keywords: Cure; Control; RTM; Thermal gradients; Heat transfer in a mold

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1. Introduction

Resin transfer molding (RTM) is one of the most efficient and attractive processes for high performance composite materials with low cost manufacturing. During the process, a thermoset resin is injected into a mold cavity containing a pre-placed fiber preform or a stack of fiber mats of reinforcing material in the shape of the desired part. The resin impregnates the mold cavity to occupy the empty spaces between the fibers. The mold is usually heated to initiate a curing reaction, which is an exothermic resin polymerization phenomenon that cross-links the resin and results in a composite structure.

For a composite part to meets the quality control requirements and have the desired properties and dimensions, several manufacturing hurdles need to be overcome during the mold filling stage and the curing stage. First, during the mold filling stage, the resin should occupy all available space between the fibers. Any space uncovered by the resin is known as voids or dry spots and will be detrimental to the mechanical properties of the composite [1]. In the last decade, modeling and simulation tools for the mold filling stage have helped significantly to design the complete filling of the mold by optimizing the injection location for the resin and manipulating the flow rates or the pressure of the resin [1–11]. The curing stage requires invoking the initiation of the cure reaction and then managing the heat evolved from the part to avoid large thermal gradients and consequently residual stresses that could lead to shrinkage and warpage and lack of dimensional tolerance. Models for resin cure

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Nomenclature

c_p	thermal heat capacity (J kg^{-1} K^{-1})
dT	percentage temperature difference for the non optimized cycle
dT_{opt}	percentage temperature difference for the optimized cycle
dα	percentage conversion difference for the non-optimized cycle
dα_{opt}	percentage conversion difference for the optimized cycle
dt	percentage processing time difference
H_r	reaction heat (J kg^{-1})
$H(t)$	differential supplied heat (W m^{-2} s^{-1})
k_z	thermal conductivity (W m^{-1} K^{-1})
max($\dot{\alpha}$)	maximum reaction rate (1 s^{-1})
$\Re$	dimensionless reaction rate
T	temperature (°C)
T_0	starting temperature (°C)
t	time (s)
t_p	processing time (s)
t_{popt}	processing time for the optimized cycle (s)
t_c	conductive time (s)
t_r	reaction time (s)
t_w	time for the crossing of the composite and mold temperatures (s)
Q	supplied heat (W m^{-2})
V_f	fiber volume fraction
z	extension (m)
α	conversion
$\dot{\alpha}$	rate of reaction (s^{-1})
α_d	thermal diffusivity (m^2 s^{-1})
δ	half mold cavity thickness (m)
ΔT_a	adiabatic temperature raise (K)
ΔT_{max}	maximum temperature increase (K)
θ	dimensionless temperature
ρ	density (kg m^{-3})
τ	dimensionless time
c, f, r	suffix for the composite, fiber, resin
A, B, C, D	suffix for the monitored locations
A	dimensionless parameter
B	dimensionless parameter

have been developed and applied to predict the curing and temperature history of the composite during the curing stage [10–14]. In situations where cycle times are of paramount concern, the mold is usually pre-heated to aid the resin flow, the filling process itself could be non-isothermal coupling the flow and cure behavior. Models and simulations for coupled situations are complicated but have been addressed in the literature [15–21].

In most cases, one would like to fill the mold with the resin and then initiate cure because if the resin starts to cross-link, its viscosity will increase rapidly and it will become increasingly difficult to push the resin into spaces between the fibers creating a network of undesirable voids in the composite. Hence, this paper will address cure only and assume that the empty spaces in the mold cavity are completely filled with the resin.

The cure cycle and the temperature history of the composite can be controlled and managed by designing and optimizing the temperature profile applied to the mold walls. Integrated use of process modeling and numerical simulations, experimental validation and advanced sensors serve as useful tools to achieve this goal [22–24]. In recent years, to acquire real-time information about the process, sensors that monitor both the filling and the cure advancement have been developed. These sensor systems are based on different operating principles such as frequency dependent electromagnetic sensor [22], fiber optic systems [23], and conductive filament grids [24]. Capability to monitor temperature and cure will allow for the possibility of control by modifying the boundary conditions (the mold wall temperatures) during the curing stage.

It should be emphasized that one of the most critical issues during the curing stage is the presence of temperature and conversion gradients through the composite part. In fact, a non-uniform development of the cure reaction could induce strong exothermal peaks and thermal differences along the thickness. This would lead to residual stresses in the composite part that could be detrimental. Due to the poor thermal conductivity of most of thermoset polymer, this scenario will get even worse if one wants to manufacture thick composite parts. Hence, a good RTM thermal/cure control will extend RTM application to thicker parts and reduce the cycle time. This control methodology can be realized by identifying the proper mold wall temperature profile to induce a uniform development of the polymerization reaction and temperature distribution before the irreversible gelling takes place.

In this study, the heat transfer phenomena occurring during the RTM composite cure are analyzed and modeled. A scaling analysis of the energy balance equation has been performed to estimate the relative relevance between the two competing phenomena, heat conduction and resin polymerization. A cure optimization methodology has been defined and a simple procedure has been developed to adjust the mold wall temperatures that induce a uniform activation of the polymerization reaction before the resin gels. This methodology is demonstrated through a numerical study for the cure and temperature control of a highly reactive polyester resin in a rectangular mold. The generality of the approach is explored by changing the fiberglass properties and the mold cavity thickness.

2. Mathematical modeling

Consider a flat rectangular mold that is filled with fiber preforms and saturated with resin and is being heated through the mold walls to initiate cure. The model will consider two relevant phenomena, the heat transfer through the mold walls in and out of the composite and the curing of the resin that will eventually solidify the part. Fig. 1 shows the schematic of the part (1 m long and 10 mm thick). We can assume that the temperature variation in the width and the length direction is negligible as compared to the thickness direction. Sensors, A, B, C, D are numerical probes established at the center, 25% of half the thickness from the center, midway between the center and the wall and 25% of half the thickness from the wall, respectively.

The composite cure stage in the RTM manufacturing process is characterized by the progress of the exothermal cure reaction which is activated by the conductive heat transport from the heated mold walls. During this stage the liquid resin cross-links releasing the heat. The degree of cross-linking is referred to as degree of cure. This phenomenon can be described by the following energy balance equation, which includes both the conductive term and cure reaction contribution:

$$\rho_c c_{pc} \frac{\partial T_c}{\partial t} = k_{zc} \frac{\partial^2 T_c}{\partial z^2} + \rho_r H_r (1 - V_f)\dot{\alpha}, \tag{1}$$

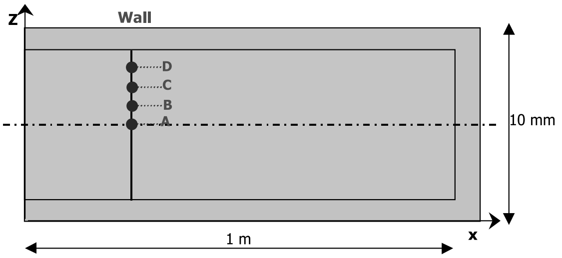

Fig. 1. Schematic representation of the analyzed system.

where the suffices r, f and c refer to the properties of the resin, the fibers and the composite, respectively, $\dot{\alpha}$ is the rate of the reaction, H_r is the heat generated by the curing reaction, V_f is the fiber volume fraction, ρ, c_p and k are the density, the heat capacity and the thermal conductivity. Note that conduction in the in-plane direction has been neglected, as the part dimensions in plane are usually one to two orders of magnitude larger than the thickness direction.

Eq. (1) is coupled to the resin kinetic model that describes the rate at which the resin cures and is a function of the degree of cure, time and temperature. Thus, one must solve the following system of differential equations:

$$\frac{\partial T_c}{\partial t} = \frac{k_{zc}}{\rho_c c_{pc}} \frac{\partial^2 T_c}{\partial z^2} + \frac{\rho_r H_r (1 - V_f)}{\rho_c c_{pc}} \dot{\alpha}, \tag{2a}$$

$$\frac{d\alpha}{dt} = \dot{\alpha} = f(\alpha, t, T). \tag{2b}$$

The energy balance equation (2a) is characterized by three terms; the change in internal energy of the composite, the conduction of heat through the composite and generation of heat within the composite due to the exothermic reaction. There are more than one characteristic timescales in this equation. The conductive time, t_c, is given by

$$t_c = \frac{\delta^2}{\alpha_d}, \tag{3}$$

where $\alpha_d = k_{zc}/\rho_c c_{pc}$ is the composite thermal diffusivity and δ is the half mold cavity thickness.

This timescale usually describes the rate at which the heat propagates through a medium due to conduction [25].

The other timescale in the above system of equations in the reaction time that can be defined by the maximum rate of reaction attained during the process

$$t_R = \frac{1}{\max(\dot{\alpha})}, \tag{4}$$

which can be conceptualized as a sort of average time necessary to attain the composite consolidation. The relative importance between the two phenomena is investigated by performing a scaling analysis of the energy balance equation (2a). Table 1 reports the chosen

Table 1
Dimensionless variables

Length	$\zeta = z/\delta$	δ half mold thickness
Time	$\tau = t/t_p$	t_p global processing time
Temperature	$\vartheta = (T - T_0)/\Delta T_{\max}$	$\Delta T_{\max} = T_{w\max} - T_0 + \Delta T_a$ T_0 temperature at the end of mold filling $T_{w\max}$ maximum wall temperature
Reaction rate	$\Re = \dot{\alpha}/\max(\dot{\alpha})$	$\max(\dot{\alpha})$ maximum reaction rate

dimensionless variables, where ΔT_a represents the increase in temperature of the composite due to the heat of reaction, H_r, under adiabatic conditions,

$$\Delta T_a = \frac{\rho_r(1 - V_f)H_r}{(\rho c_p)_c} \tag{5}$$

and t_p represents the processing time, i.e. the time to reach a sufficient high degree of cure. (The resin has cross-linked to the extent that it has solidified and can be removed from the mold, e.g. $\alpha = 0.9$.)

The dimensionless form of Eq. (1) can be recast as

$$\frac{\partial\vartheta}{\partial\tau} = \frac{t_p}{t_c}\frac{\partial^2\vartheta}{\partial\zeta^2} + \frac{t_p}{t_R}\frac{\Delta T_a}{\Delta T_{\max}}\Re. \tag{6}$$

All the dimensionless variables are defined in Table 1. Eq. (6) exhibits two dimensionless parameters:

$$A = \frac{t_p}{t_c} \tag{7}$$

is the ratio between the processing and the conductive time and

$$B = \frac{t_p}{t_R}\frac{\Delta T_a}{\Delta T_{\max}} \tag{8}$$

characterizes the influence of the polymerization reaction on the temperature histories through the thickness of the composite. It can also be thought of as the ratio between the heating rate due to the exothermal cure reaction and the global heating rate. $\Delta T_{\max}$ in Table 1 is the temperature difference between the initial mold wall temperature and the maximum wall temperature.

3. Methodology to minimize temperature gradients

The optimization of the composite cure process relies on minimization of the temperature gradients through the thickness of the composite at the instant the resin gels and solidifies. Lower temperature gradients during the polymerization lead to lower thermal residual stresses and less warpage and shrinkage and better dimensional tolerance of the part. The only variables one can control to drive the process towards this scenario are control of the cure chemistry or adjustment of the mold wall temperature boundary conditions to influence the temperature distribution through the thickness of the composite. Our focus will be to predict the mold wall temperature history that will enable generation of a uniform activation of the cure reaction both along the thickness and the length of the mold cavity.

The method has proposed for composites that have filled under isothermal mold filling. The mold filling under constant temperature is common especially for highly reactive resins where it is important for the resin to impregnate the fiber preform and occupy all the empty spaces between the fibers before the cure reaction activates and induces a sharp increase of the resin viscosity and jeopardizes the impregnation process. Further, this assumption ensures that the temperature profiles during the composite consolidation are not affected by the temperature filling history and, consequently, no temperature differences along the filling direction axis are expected. This simplify our analysis and we need to consider temperature variations only along the thickness direction.

The schematic of the implemented methodology is reported in Fig. 2. At first, a linear increase of the mold wall temperature from room temperature T_0 to the temperature $T_0 + \Delta T_a$ has been imposed until the end of the cure reaction for the selected resin system. The temperature evolution along the thickness has been determined by integrating numerically the differential equation ((2a) and (2b)) (for details of numerical solution procedure see [10]).

If thermal gradients are observed across the thickness of the composite part (see Fig. 4), a new mold wall temperature profile is imposed by adjusting the maximum imposed wall temperature and introducing an intermediate plateau. The maximum wall temperature and the plateau level and the duration of the plateau were set by employing a methodology based on the rate of energy balance principle.

In this methodology, first, the conductive flux supplied to the system is calculated until time t_w where the composite thermal profiles cross the mold temperature profile (see Fig. 4)

$$Q = \int_0^{t_w} H(t)\,\mathrm{d}t \tag{9}$$

in which

$$H(t) = \frac{k_{zc}}{\delta/4}(T_{\text{wall}} - T_D), \tag{10}$$

where T_D is the temperature of the location at 25% of half the thickness from the wall. As H(t) is the flux from the wall, we chose the closest node to the wall (D) to calculate the flux. Once Q is determined, the maximum temperature increase to be set for the wall is calculated as follows:

$$\Delta T = \frac{Q}{(\rho c_p)_c\delta}. \tag{11}$$

Thus, the maximum wall temperature is set by adding the estimated temperature increase ΔT to the previous value ($T_0 + \Delta T_a$). The plateau is introduced at temperature T_1 where the contribution of heat from the reaction is insignificant. The plateau is set for a duration of time that allow the composite to achieve temperature values across the composite thickness that are close to each other. This is equivalent to heating the composite from

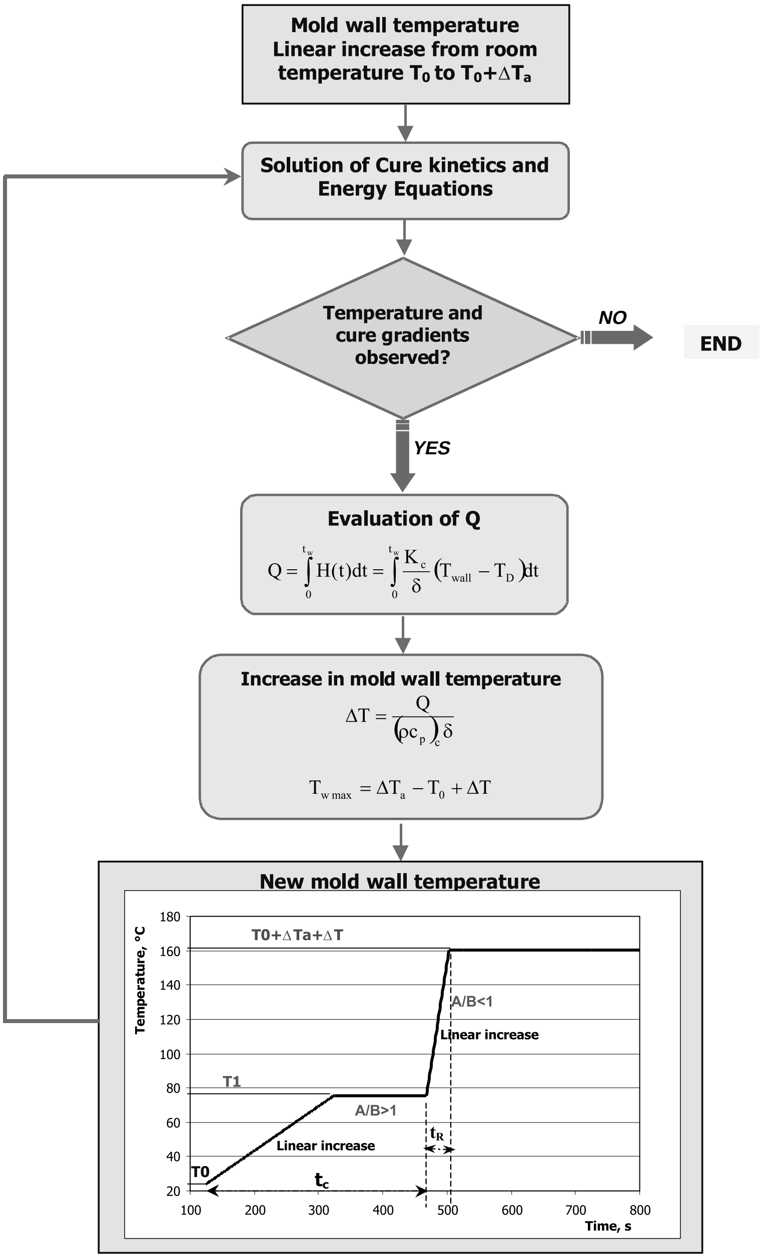

Fig. 2. Flow chart of the optimization methodology.

the mold walls through its thickness until a steady state is reached across the thickness but before the reaction kicks in. The conductive time is used as the initial guess to set the plateau duration, which is then, verified by the direct comparison between the through thickness temperatures during the numerical calculations. The ratio of the two dimensionless groups A/B and $\Delta T_{\max}$ are calculated separately in two ramp regions. During the first ramp, as the reaction rate is small, t_R will be high and hence $A/B > 1$. In the second region, t_R is small due to the high reaction rate and hence A/B is small. In the first region A/B is greater than unity indicating a dominance of the conductive heat transport as compared to the polymerization reaction. In the second ramp, which we label as the reaction zone, the reaction contribution becomes more significant as the heat of reaction is evolved, the ratio A/B is less than unity indicating a negligible contribution due to the heating of the mold walls. For a given temperature rise, i.e., $(T_0 + \Delta T_a + \Delta T) - T_1$, the slope of the ramp to be applied in the reaction zone is determined by evaluating the time the reaction takes to reach its exothermal peak at the center location, characterized by an higher rate of curing. In this way, since the location D closest the mold wall is heated up by at the same rate of the center, lower thermal gradients are expected.

4. Example to demonstrate the methodology

The proposed methodology is demonstrated with an example that enables the reduction of temperature gradients through the thickness of a composite for a highly reactive resin by selecting appropriate temperature history of the mold walls. The resin selected is a reactive polyester resin infiltrated in a random glass fiber preform (fiber volume fraction: 0.32) placed in an aluminum rectangular mold. The resin cure kinetic model for the resin is given by [7]:

$$\dot{\alpha} = K_{\mathrm{p}}(1-\alpha)[R], \tag{12}$$

$$\frac{\mathrm{d}[R]}{\mathrm{d}t} = 2fK_{\mathrm{d}}[I], \tag{13}$$

$$\frac{\mathrm{d}[I]}{\mathrm{d}t} = -K_{\mathrm{d}}[I], \tag{14}$$

where

$$K_{\mathrm{d}} = A_{\mathrm{d}} \exp\left(-\frac{E_{\mathrm{d}}}{RT}\right), \tag{15}$$

$$K_{\mathrm{p}} = A_{p0} \exp\left(-\frac{E_{p0}}{RT}\right)\left(1-\frac{\alpha}{\alpha_{\mathrm{f}}}\right)^{m}. \tag{16}$$

Table 2 reports the values of the kinetic parameters in Eqs. (12)–(16). See Fig. 3 for the plot of reaction rate with respect to the time for the above kinetic model at various temperatures is shown.

Table 2
Kinetic parameters

Parameter	Value
f	0.1
α_{f}	1.0
A_{d}	5.55×10^{16}
A_{p0}	0.38×10^{10}
E_{d} (J/mol)	1.41×10^{5}
E_{p0} (J/mol)	4.27×10^{4}
$[I]_t = 0$	0.005208
$[R]_t = 0$	0
H_{r}	2.44×10^{5}

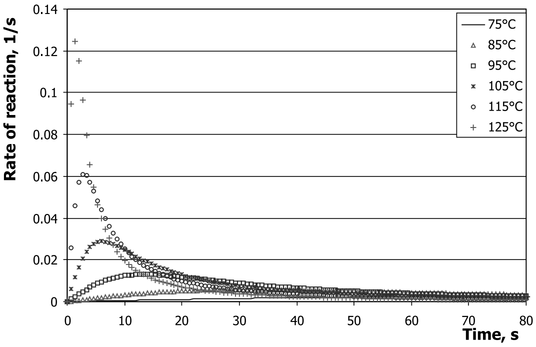

Fig. 3. Rate of reaction of the analyzed resin system.

Table 3
Material properties

Properties	Resin	Fiberglass	Aluminum
Density (Kg/m^3)	1100	2560	2643
Heat capacity (J/kg K)	1680	670	837
Thermal conductivity (W/m K)	0.168	0.0335–0.417	206

Table 4
Case characteristics

Case	Composite thermal diffusivity (m^2/s)	Mold cavity thickness (m)
1	7.2×10^{-8}	0.0101
2	7.2×10^{-8}	0.013528
3	7.2×10^{-8}	0.00676
4	1.37×10^{-7}	0.0101
5	1.37×10^{-7}	0.013528
6	1.37×10^{-7}	0.00676

In order to explore the capabilities of the method, several numerical simulations were performed for different values for the composite thermal diffusivity and the mold cavity thickness that do effect the characteristic heat conduction rate. Tables 3 and 4 report the material properties used. For all case studies, the following procedure was adopted. First, the temperature and degree of cure (conversion) profiles are evaluated at four locations A, B, C, D as shown in Fig. 1 by imposing the mold wall temperature history as shown in Fig. 4 which we call as case 1, in which no attempt is made to optimize this profile to reduce the temperature gradients across the thickness. The base case, case 1, is characterized by a mold thickness of 0.0101 m and a composite thermal diffusivity equal to 7.2×10^{-8} m^2/s. For the remaining cases, the mold thickness has been changed by ±30% and the higher composite thermal diffusivity is applied. The maximum wall temperature was set at 125.2 °C. It is the sum of the initial temperature (24 °C) and the adiabatic temperature increase (101.2 °C) calculated using Eq. (5).

The results exhibited in Figs. 4 and 5 show that no uniform activation of the cure reaction was observed. In fact, the polymerization reaction initiates first near the

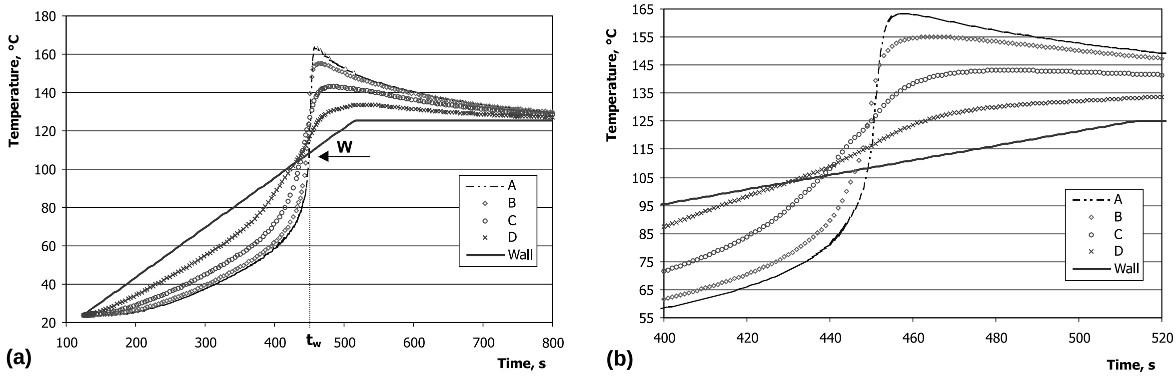

Fig. 4. (a) Composite and mold wall temperature profiles in the case of non-optimized cure cycle (parameters used from case 1), (b) enlarged plot near the area of interest.

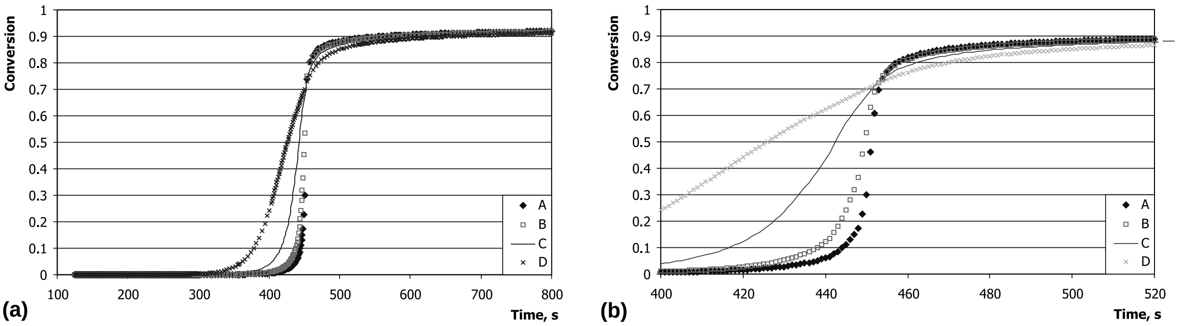

Fig. 5. (a) Degree of cure profiles in the case of non-optimized cure cycle (sase 1), (b) enlarged plot near the area of interest.

mold wall interface (location D) and then propagates towards the center resulting in different resin conversion evolution profiles and strong exothermal peaks across the composite thickness at different times. These phenomena are undesired as they will cause large temperature gradients across the thickness and will be detrimental for the properties of the manufactured parts. In particular, to increase the final mechanical properties and to avoid the residual stress generation, the cure reaction control to minimize temperature gradients should occur before the resin gels (that is before the resin conversion is approximately 0.7 for the selected resin) after that the composite consolidation takes place.

In order to optimize the curing phase, a two-step methodology was adopted. In the first step, which is called the conduction zone, the mold wall temperature was raised to a plateau and held until the temperature across the thickness were close to uniform. In the second step, called the reaction zone, the mold wall temperature was further increased to a higher temperature to complete the cure reaction. The heat flux supplied to the system and the temperature increases were evaluated with Eqs. (9) and (10), respectively. Table 5 reports the calculated Q and ΔT values for each case.

Table 5
Q and ΔT values (Eq. (9))

Case	Q (W/m^2)	ΔT (°C)
1	323822	35.36
2	380691	31.17
3	236794	38.8
4	351504	38.38
5	436943	35.78
6	238566	39.1

With reference to case 1, the mold wall temperature was varied linearly and held at 75 °C where the reaction contribution is insignificant, i.e. the ratio between the two dimensionless group A/B is 1.83. The plateau level has been set at 75 °C by observing the thermal profiles of the non optimized case (see Fig. 4): the temperature profiles of the four monitored locations show a change of slope for values around 75 °C after which the increase is very fast due to the strong polymerization reaction development. The dwell time at 75 °C was calculated to be 145 s. This time was calculated by subtracting the time it takes to reach 75 °C from the conductive time (Eq. (3)). Then, a fast (35 s) linear increase was imposed

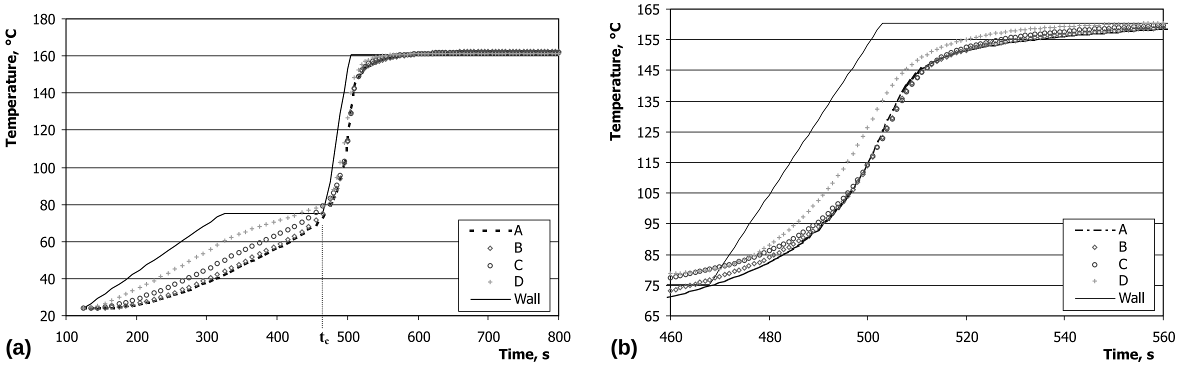

Fig. 6. (a) Composite and mold wall temperature profiles in the case of optimized cure cycle (sase 1), (b) enlarged plot near the area of interest.

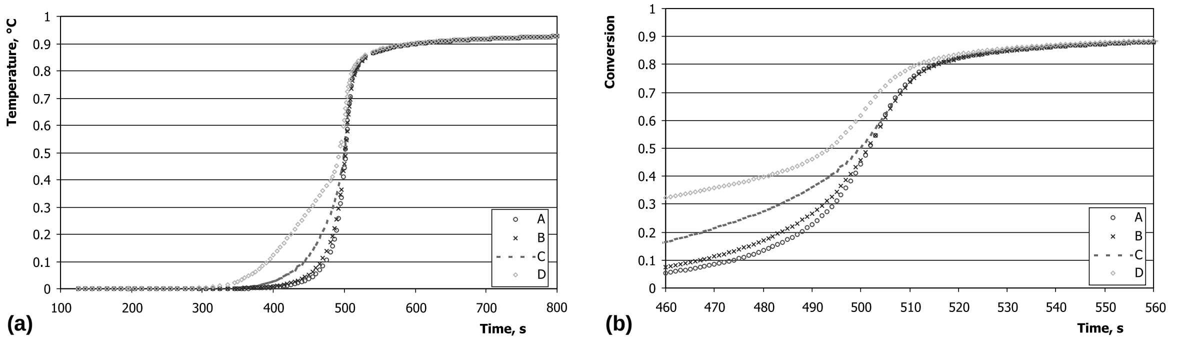

Fig. 7. (a) Degree of cure profiles in the case of optimized cure cycle (case 1), (b) enlarged plot near the area of interest.

until 160.56 °C was reached which being the sum of the initial temperature T_0 (24 °C), the adiabatic temperature increase ΔT_a (101.2 °C) calculated from Eq. (5) and the temperature difference, ΔT (Eq. 11). To have a uniform development of the reaction through the part, the slope of this ramp was determined to be 35 s which is the time the reaction takes to reach the exotherm peak at the center.

Figs. 6 and 7 show the calculated temperature and conversion profiles with the optimized cure cycle. No temperature gradients along the part are observed in the reaction zone. Further, before the achievement of the gel point (0.68), the cure reaction develops uniformly suggesting the minimal residual stresses in the final part.

The same procedure has been applied to other cases. To emphasize the effectiveness of the methodology, maximum temperature and conversion difference percentages between the center (A probe) and the location D (see Fig. 1) have been evaluated in the reaction zone after 0.6 conversion before the gel point (0.68) was achieved as follows:

$$\mathrm{d}T = \frac{T_\mathrm{D} - T_\mathrm{A}}{T_{\mathrm{A\,max}}}, \tag{17}$$

$$\mathrm{d}\alpha = \frac{\alpha_\mathrm{D} - \alpha_\mathrm{A}}{\alpha_{\mathrm{A\,max}}}, \tag{18}$$

where T_A, T_D, α_A, α_D are the temperature and the conversion at the A and D locations, respectively, $T_{\mathrm{A\,max}}$ and $\alpha_{\mathrm{A\,max}}$ are the maximum temperature and conversions at the mold center in the reaction zone.

Table 6 reports the temperature and conversion difference percentages for each case before $(\mathrm{d}T, \mathrm{d}\alpha)$ and after the optimization $(\mathrm{d}T_\mathrm{opt}, \mathrm{d}\alpha_\mathrm{opt})$. It should be observed that the temperature differences between the center and the mold wall locations decreased signifi-

Table 6
Temperature and conversion % differences of the non-optimized and the optimized cases (opt)

Case	$\mathrm{d}T$	$\mathrm{d}T_\mathrm{opt}$	$\mathrm{d}\alpha$	$\mathrm{d}\alpha_\mathrm{opt}$
1	25.6	4.9	11.6	11
2	25.1	10	20	7
3	22.4	3	18	15
4	23.4	5.3	16	15
5	25.3	6.4	18	17
6	16.8	3.6	15	12

Table 7
Processing time % differences between the non-optimized and optimized (opt) cases

Case	t_p	t_popt	dt_p (%)
1	660	462	30
2	660	579.5	12.2
3	660	365	44.7
4	660	379	42.5
5	660	442.6	32.9
6	660	334.6	49.3

cantly due to the application of the methodology. The highest value of 10% in case 2 was induced by the higher conductive time (635 s) that caused the overlay of the polymerization and conduction phenomena.

Finally, since, after the optimization, the cure reaction occurred at higher temperature, a reduction of the processing time was observed in all cases as reported in Table 7, where t_p and t_popt are the times to reach 0.9 conversion in the non-optimized and optimized cases, respectively, and dt_p is their percentage difference.

5. Dimensionless parameters

The RTM composite consolidation is determined mainly by two phenomena: conductive heat transfer from the mold walls to the resin–fiber system and the polymerization reaction. A scaling analysis of the energy balance equation including both the conduction and the reaction term revealed two dimensionless parameters: A, the ratio between the processing and the conductive time and B, the ratio between the exothermal reaction and the global heating rate. Therefore, the ratio A/B could be assumed as a measure of the relevance between the conduction and the cure reaction, being greater and lower than unity in the case of major contribution of the conduction and reaction, respectively.

The RTM cure optimization has been based on the determination of the proper mold wall temperature to reduce the thermal gradients across the composite thickness. The introduction of a plateau for the mold wall temperature before the cure reaction activation allowed the identification of two zones: a conduction zone and a reaction zone, characterized by the ratio A/B greater and lower than unity, respectively. To confirm these considerations, the ratio A/B has been calculated for the optimized cure cycles. Table 8 shows the ratio A/B both in the conduction and in reaction zone for all optimized cure cycles. As expected, except one case, the values of A/B are greater than unity in the first zone (range 1–8.5) and less than unity in the second zone (range 0.06–0.45). In the conduction zone, the ratio A/B around unity has been observed in case 2 that is characterized by the higher conductive time as a result of the low composite thermal diffusivity and higher mold thickness. Therefore, due to the low conduction rate, the cure reaction activation zone crossed over the conductive heat transport zone which caused a more complex control of the cure cycle. Since the A/B ratio implies the process controllability by using heat conduction, a low A/B ratio case is expected to be less improved after the optimization. In other words, while employing the heat conduction to manipulate the temperature history of the composites, the A/B ratio can be considered as the index for the controllability of using this method. Tables 6–8 evidence this hypothesis.

6. Conclusion

The heat transfer phenomena occurring during the RTM cure stage have been modeled by a scaling analysis of the energy balance equation accounting for both the conduction and the exothermal reaction. Two dimensionless groups have been identified, first is the ratio between the processing and the conductive time and second is the relevance of the cure reaction on the composite thermal profiles.

To optimize the cure stage, a new methodology has been developed allowing to separate the conduction and the reaction contribution and to reduce the temperature gradients induced by a non-uniform activation of the polymerization through the composite part. Two optimization strategies have been applied in the conduction zone and the reaction zone, respectively, in order to lower the temperature gradients of the composites

Table 8
Dimensionless A/B ratio in the conduction and reaction zones for the optimized cycles

Case	Composite thermal diffusivity ($\mathrm{m^2/s}$)	Mold cavity thickness (m)	A/B conduction zone	A/B reaction zone
1	7.2×10^{-8}	0.0101	1.83	0.103
2	7.2×10^{-8}	0.013528	1.03	0.06
3	7.2×10^{-8}	0.00676	4.12	0.23
4	1.37×10^{-7}	0.0101	3.49	0.196
5	1.37×10^{-7}	0.013528	1.96	0.11
6	1.37×10^{-7}	0.00676	8.46	0.435

during the resin gelation and consolidation. The method capability and generality has been demonstrated by changing the composite thermal diffusivity and the mold cavity thickness affecting the rate of the conductive heat transport. Temperature and conversion differences along the thickness have been calculated for the optimized cure cycles and shown to reduce thermal gradients substantially as compared to non-optimized heating of the composite. This method will prove useful to improve the quality of composite parts manufactured by RTM process.

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