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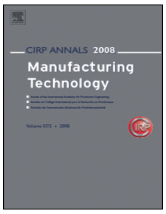

A step-wise numerical thermal control method for advanced composite curing process using digital image based programming

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Accurate temperature control is required in advanced heat treatment processes such as composite curing. The crux is how to determine the appropriate heat sources which would result in the required temperature distribution during part heating process. This paper presents a new thermal control method using digital image based programming, which efficiently and accurately estimates required heat sources and controls temperature distribution in a step-wise numerical manner. The method was validated in both simulation and real heating tests for microwave curing of composites, showing excellent temperature uniformity and consistency with given target temperature profiles, compared with existing technologies.

Process control; Temperature; Composite curing

1. Introduction

A great deal of manufacturing processes require heat treatment such as curing and annealing, which are essentially to control temperature distribution across parts being heated over a specified cycle. Improper temperature distribution may cause quality degradation [1], distortion in shape and excessive residual stress within processed parts [2]. Therefore, accurate thermal control is important to meet the growing demand for quality and capacity of heat processed parts. Composite curing is a typical process that requires accurate temperature control. Autoclave curing is still preferred in manufacturing high standard parts due to its high stability and compatibility. However, its conductive heating principle makes flexible thermal control difficult.

Newly emerged curing systems with selective heating mechanisms, such as microwave heating [3, 4], electrical resistance heating [5], and rapid high performance moulding [6], could generate controllable heating patterns for different requirements. These rapid and flexible heating principles potentiated highly specialized curing regimen with customized temperature profiles [7]. However, it is still difficult to precisely control temperature distribution by these methods, especially for microwave curing, despite their high efficiency and flexibility. Non-uniformity of temperature distribution always occurs in the form of hot and cold spots on parts due to uneven resonance of electromagnetic field in the cavity [8]. Efforts were made to alleviate the above deficiency by either redesigning the cavity [9], applying a dynamic motion between the part and the electromagnetic field [10], or compensating with a synthetic opposite heating pattern [11]. These attempts, especially the pattern compensation strategy, were effective only in certain temperature ranges due to the lack of comprehensive formulation of heat transfer process. Such methods relied on tedious calibration of hundreds or even thousands of combinations of heating patterns, thus are still distant from industrial applications.

We argue that effective and accurate thermal control depends primarily on the relationship between the resultant temperature distribution and the heating patterns continuously applied to the part during heating process. The sophisticated heat dissipation and diffusion during heating will result in a dynamic and time-delayed temperature distribution on heated part. Therefore, it is important to be able to accurately estimate the appropriate heat sources in advance, to ensure that the resultant temperature distribution approximates the target temperature profile. The estimation of required heat sources based on pre-specified target temperature distribution profile is mathematically ill-posed due to the non-uniqueness of the solution. Efficient iteration based algorithms are required to solve this inverse problem, which had been studied for decades using various data analytical methods [12, 13]. There were however no applicable methods to facilitate industrial level heating control due to high computational cost.

We propose to formulate the problem as determining the required heat sources with respect to the target temperature profile along with heating time. By continuously applying appropriate heat sources, the resultant temperature distribution at corresponding time can be achieved. The pattern of the heat sources can be realized by numerically controlling the heat suppliers, e.g., magnetrons installed on a microwave curing cavity. The target temperature profile on the part surface can be programmed by allocating appropriate power to individual heat suppliers at discrete time intervals, called *power states*. The proposed method is named *numerical thermal control*, which requires a new computing algorithm for efficient and accurate estimation of the required heat sources to achieve the corresponding optimal target temperature profile. Given this, a digital image programming algorithm was developed to entirely formulate the resultant temperature distribution in unified digital image domain. In this way, the inverse problem of estimating required heat source and then power state of each heat supplier could be resolved using image processing pipeline. Therefore, numerical thermal control can be efficiently and accurately conducted via the computation of power states along heating time.

2. Problem definition and overview of the proposed method

We set out to achieve a target temperature profile assigned to a composite part, by calculating the time-dependent power states of

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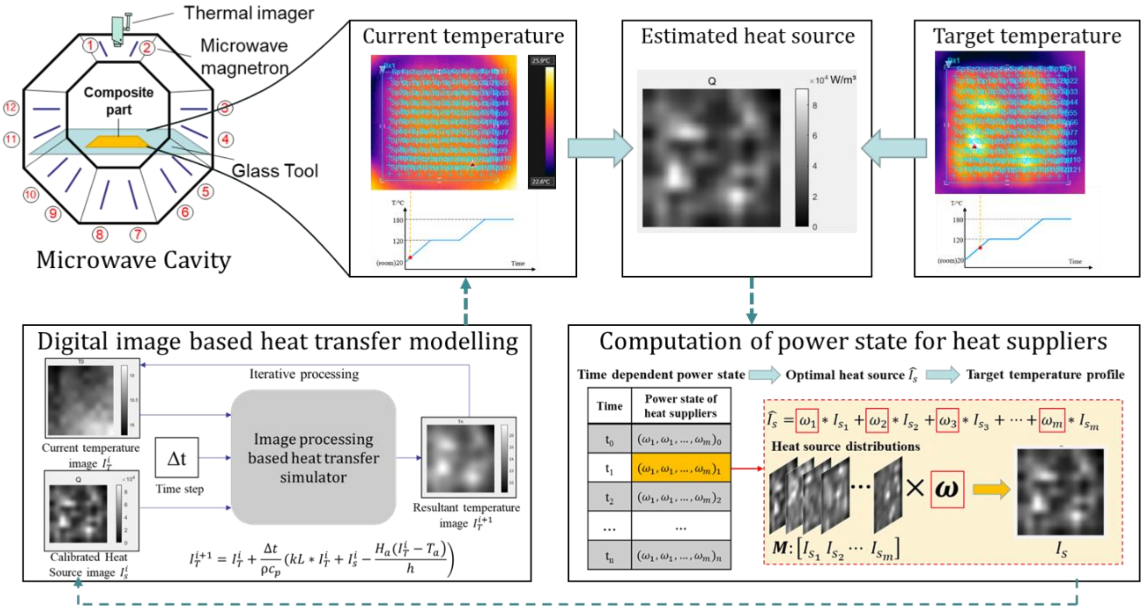


Figure 1. An overview of the numerical thermal control method for composite curing process using digital image based programming.

individual heat suppliers, i.e., the input power magnitude of each microwave magnetron. Figure 1 provides an overview of the idea.

While the heat source generated by each heat supplier is in the form of a unique and static distribution over the part surface, its induced temperature distribution, which can be accurately measured using a calibrated thermal imager, is dynamically changing according to heat transfer mechanism. As long as the heating control is instantly effective, i.e., changing the input power of heat supplier directly affects the heating rate, the computed power state can be numerically imported to the heat supplier thus to control the heating process. To achieve this, we proposed to establish a uniform domain, the discrete digital image domain with evenly sampled pixels, for predicting temperature distribution and computing the time dependent power state of the heat supplier. The method of numerical thermal control includes three main tasks: heat transfer simulation, heat source estimation and power state computation. As shown in Figure 1, an image processing pipeline was constructed to numerically simulate heat transfer process to predict transient temperature distribution, given that heat diffusion can be mathematically equivalent to blurring a thermographic image. By taking the advantage of this pipeline, heat source distribution as represented in the same image domain could be quickly and accurately estimated via an inverse computation. Eventually, the power state of each heat supplier could be computed and used to numerically control the heating process in accordance with the target temperature profile.

3. Modelling and control of time varying temperature distribution using digital image based programming

3.1 Heat transfer modelling based on image processing

Given a thin shell part P placed inside a large cavity, we could simulate a simplified heat transfer process by defining the time varying temperature distribution $T(x,y,t)$ in the surface domain $S(x,y) \subset$ P of the part, assuming that the temperature gradient $\frac{\partial T}{\partial z}$ along thickness direction can be ignored. The differential heat conduction could thus be expressed as:

$$\rho c_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + q_s - q_d \tag{1}$$

where ρ, c_p and k are the density, specific heat capacity and in-plane thermal conductivity, respectively. q_s is the heat source distribution generated by the heat supplier. q_d is the heat dissipation distribution from the part surface to the air that can be formulated as a heat convection function in Newton's law of cooling:

$$q_d = \frac{H_a A(T - T_a)}{V} = \frac{H_a(T - T_a)}{h} \tag{2}$$

where H_a is the heat transfer coefficient, T_a is the temperature of surrounding air, and h is the thickness of the part.

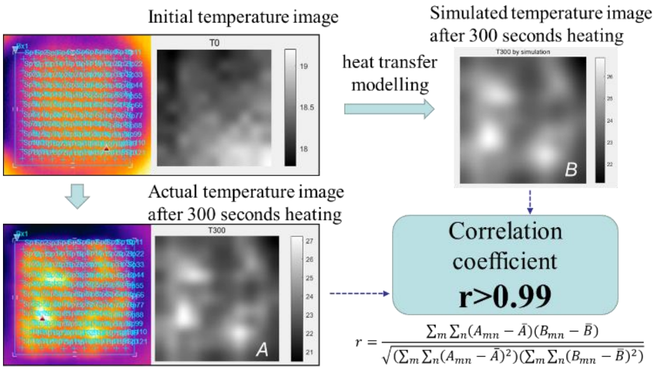


Figure 2. Accuracy evaluation for heat transfer model using image based programming.

For any particular time, the temperature distribution $T(x,y)$ over the surface domain could be faithfully represented by a grayscale image I_T (see Figure 1), where each pixel $p_{i,j} \in I_T$ stores the temperature value of the corresponding location. Meanwhile, the heat source distribution q_s could be represented in the same domain as I_s. In this way, the differential heat conduction process could be uniquely converted to iterative image processing step:

$$I_T^{i+1} = I_T^i + \frac{\Delta t}{\rho c_p}\left(kL * I_T^i + I_s^i - \frac{H_a(I_T^i - T_a)}{h}\right) \tag{3}$$

where $\Delta t = t_{i+1} - t_i$ is a small time step for iteration, L stands for the discrete Laplacian kernel represented in a 3 × 3 matrix. As long as the initial temperature distribution I_T^i and the heat source distribution I_s are provided, the changed temperature I_T^{i+1} as the result of the applied heat source I_s can be directly determined by Eq. (3) with high accuracy and efficiency. The temperature predicting accuracy could be evaluated by comparing the correlation coefficient between simulated and actual thermal image, which could reach over 99% as shown in Figure 2. Nevertheless, the actual temperature I_T should follow a pre-specified target temperature profile. The problem is thus inversely defined as the optimization of the time dependent heat source distribution $I_s(t)$, also referred to as heat source estimation.

3.2 Heat source estimation

The actual curing temperature distribution should be controlled to be close to the target temperature profile by continuously adjusting the power state of the heat suppliers to control the heat source at discrete time intervals. Therefore, for a time interval from t_0 to t_n, the initial temperature at t_0 is known and represented as I_T^0, while the target temperature image is set according to the target temperature profile as I_T^n. The crux is to estimate the required heat source distribution I_S^0 that results in the temperature distribution to I_T^n at time t_n. We intend to solve this inverse problem in an iterative manner, by taking the advantage of the image processing based modelling, which is accurate and of high computational efficiency. The estimation of heat source I_S^0 starts with an initial value by ignoring the in-plane heat conduction process. Although this initial value barely satisfies the estimation accuracy, we can use it to apply to a heat transfer simulation to obtain the resultant temperature $\widehat{I_T^n}$. The discrepancy between $\widehat{I_T^n}$ and target I_T^n will trigger an update of the estimated heat source, which will gradually converge to the ground truth after several iterations. The application of digital image processing makes the entire computation highly efficient and accurate. The algorithm for heat source estimation is provided in Algorithm 1.

Algorithm 1. Pseudocode of image based heat source estimation

```
Input: Initial temperature image $I_T^0$, target temperature image $I_T^n$, duration of the heating process $t = t_n - t_0$.
Output: Heat source image $I_S^0$.
Method: Image based heat source estimation
define ρ, $c_p$, $H_a$;  // define essential parameters
$I_s \leftarrow \frac{\rho c_p (I_T^n - I_T^0)}{t} + \frac{H_a (I_T^n - T_a)}{h}$; //Approximate initial heat source
while 1 do
    $\widehat{I_T^n} \leftarrow$ heat_transfer ($I_T^0, I_s, t$); //Heat transfer via Eq. (3)
    similarity ← matrix_correlation($\widehat{I_T^n}, I_T^n$);
    if (similarity>0.95)
        break;
    end if
    $I_s \leftarrow I_s + \frac{\rho c_p (I_T^n - \widehat{I_T^n})}{t}$; // Update heat source image
    if (min($I_s$))<0)
        $I_s \leftarrow \max(I_s) \cdot \frac{I_s - \min(I_s)}{\max(I_s) - \min(I_s)}$; //Normalize $I_s$
    end if
end while
return  $I_S^0 \leftarrow I_s$;
```

It is noteworthy that the output heat source distribution I_s is only theoretically optimum. In practice, the heat source is induced by a weighted superposition of heat suppliers, leading us to finding the optimal power state to best approximate the required heat source distribution.

3.3 Control of time varying temperature distribution

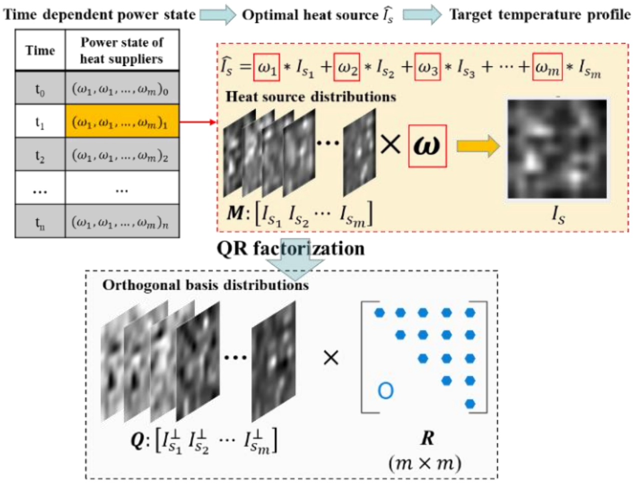
Assuming that there are m heat suppliers in the curing system, each generates a unique heat source distribution $I_{s_j}, j = 1,2, \dots, m$ at nominal power state P_N. Assuming that the power state of one heat supplier will not affect the heat source distribution induced by other suppliers. Thus, the heat supplier can be regarded as linearly independent, which is experimentally verified for microwave heating. The remaining problem is to find a weighted power ratio $\boldsymbol{\omega} = (\omega_1, \omega_2, \dots, \omega_m)$ to identify the power state, such that the weighted sum $\widehat{I_s} = \sum_{j=1}^{m} \omega_j \, I_{s_j}$ can best approximate the optimal value I_s. In this way, the time dependent temperature distribution can be controlled by setting a time varying power state to numerically control the heat suppliers. To achieve this, the heat source distribution I_{s_j} of each heat supplier under unified power state should be first estimated via Algorithm 1 with the help of a thermal imager. With the availability of I_{s_j}, the problem of finding a weighted power ratio $\boldsymbol{\omega}$ can be defined as a linear programming problem:

$$\text{Minimize } \Delta I_s = \sum_{j=1}^{m} \omega_j \, I_{s_j} - I_s$$
$$\text{s.t.}\, \boldsymbol{\omega_l} \leq \boldsymbol{\omega} \leq \boldsymbol{\omega_u} \tag{4}$$

where $\boldsymbol{\omega_l}$ and $\boldsymbol{\omega_u}$ are respectively the lowest and highest allowed power ratio regulated by the heat supplier. We propose to solve this problem by first transforming the linear independent heat source distributions I_{s_j} into orthogonal basis $I_{s_j}^{\perp}$ using QR factorization, which strives to decompose a matrix M into a product of an orthogonal matrix Q and an upper triangular matrix R. Each column of the orthogonal matrix Q stands for one orthogonal basis for the column space of M. The matrix M is constructed by reshaping each heat source image into a column vector. Once the orthogonal basis embedded in the matrix Q is computed, the weighted power ratio $\boldsymbol{\omega}$ can be derived as:

$$\boldsymbol{\omega} = R^{-1} \left[\frac{\langle I_{s_1}^{\perp}, I_s \rangle}{\| I_{s_1}^{\perp} \|}, \frac{\langle I_{s_2}^{\perp}, I_s \rangle}{\| I_{s_2}^{\perp} \|} \cdots \frac{\langle I_{s_m}^{\perp}, I_s \rangle}{\| I_{s_m}^{\perp} \|} \right]^T \tag{5}$$

A further regularization of $\boldsymbol{\omega}$ is needed to rectify the value into prescribed range, according to Eq. (4). This process of computing the power state is delineated in Figure 3, which is periodically executed to stage the optimal heating strategy for the corresponding target temperature profile. Eventually, a time dependent power state can be encoded to numerically control the curing system, as illustrated in Figure 3.

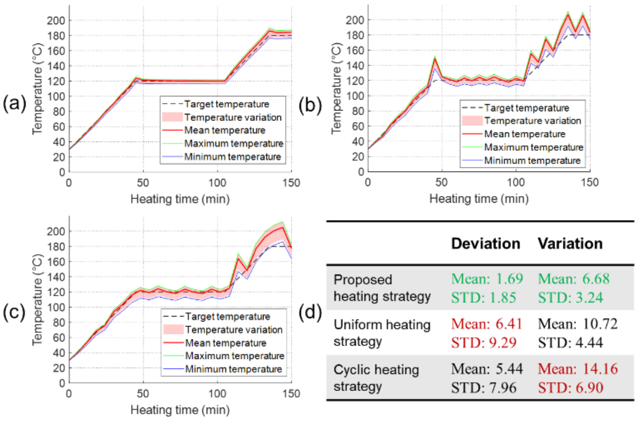


Time	Power state of heat suppliers
t_0	$(\omega_1, \omega_1, \dots, \omega_m)_0$
t_1	$(\omega_1, \omega_1, \dots, \omega_m)_1$
t_2	$(\omega_1, \omega_1, \dots, \omega_m)_2$
…	…
t_n	$(\omega_1, \omega_1, \dots, \omega_m)_n$

Figure 3. Computation of time dependent power state.

4. Results and discussions

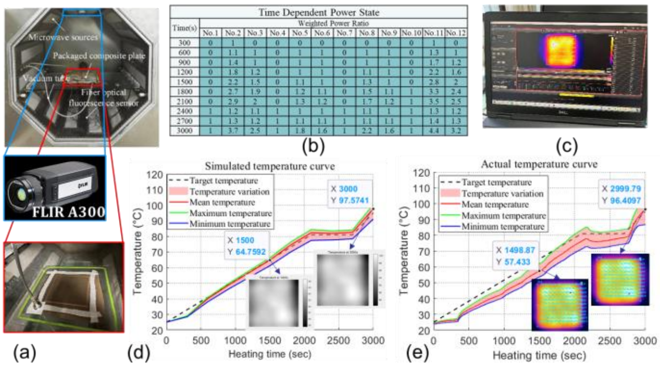
A system for planning the step-wise numerical thermal control strategy was developed to realize the proposed method. The system was capable of generating time dependent power state in both offline and online manner, upon the calibration of thermal conductivity and heat transfer coefficients. Both simulation and actual heating tests were conducted in an octagonal microwave cavity with 12 microwave magnetrons distributed on the side wall as heat suppliers. A rectangular composite part was placed inside the cavity to be heated according to a target curing temperature profile. The unified heat source distribution q_s for each magnetron was individually calibrated via a five minutes heating with $P_N = 100$ W. The step-wise power state planned for numerical thermal control is in the form of a matrix, where each row represents a weighted power ratio for a particular time interval (30 seconds for the simulation tests). Note that a smaller time interval would be recommended upon a more sophisticated temperature profile to ensure accurate thermal control. The allowable range of power ratio was set to be $\{\omega | \omega = 0 \text{ or } \omega \in [1,10]\}$, meaning that each magnetron could be powered off or powered on with 100 to 1000 watts. The output temperature was expected to align with the target profile (in black dashed line in Figure 4).



	Deviation	Variation
Proposed heating strategy	Mean: 1.69 STD: 1.85	Mean: 6.68 STD: 3.24
Uniform heating strategy	Mean: 6.41 STD: 9.29	Mean: 10.72 STD: 4.44
Cyclic heating strategy	Mean: 5.44 STD: 7.96	Mean: 14.16 STD: 6.90

Figure 4. Results of simulation: (a) proposed heating strategy; (b) uniform heating strategy; (c) cyclic heating strategy; (d) deviation and variation of induced temperature w.r.t target profile.

Three control strategies using the proposed method, uniform heating and cyclic heating respectively were employed and compared in the simulation test. Results indicated the superiority of the proposed method for its highly enhanced uniformity and consistency with the target temperature profile. Compared with baseline strategies, the proposed thermal control strategy achieved highly reduced temperature deviation (74% off) and in-plane temperature variation (53% off), thanks to the accurate and efficient optimization using image based programming.



Time Dependent Power State

Time(s)	Weighted Power Ratio											
	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12
300	0	1	0	0	0	0	0	0	0	0	1	0
600	0	1.1	1	0	1	1	0	1	1	0	1.3	1
900	0	1.4	1	0	1	1	0	1	1	0	1.7	1.2
1200	0	1.8	1.2	0	1	1	0	1.1	1	0	2.2	1.6
1500	0	2.2	1.5	0	1.1	1	0	1.3	1	0	2.8	2
1800	0	2.7	1.9	0	1.2	1.1	0	1.5	1.1	1	3.3	2.4
2100	0	2.9	2	0	1.3	1.2	0	1.7	1.2	1	3.5	2.5
2400	1	1.2	1.1	1	1	1	1	1.1	1	1	1.3	1.2
2700	1	1.3	1.2	1	1.1	1.1	1	1.1	1.1	1	1.4	1.3
3000	1	3.7	2.5	1	1.8	1.6	1	2.2	1.6	1	4.4	3.2

Figure 5. Results of actual heating: (a) experimental setup; (b) optimized power state; (c) heating process; (d) simulation result; (e) actual result.

A physical validation for heating a composite plate up to 100°C was also carried out, as shown in Figure 5(a). The entire heating process was numerically controlled by the optimized power states shown in Figure 5(b), in which the time interval was set to 300 seconds per row due to the lack of automatic controller (the upcoming power states were set manually for every 300 seconds). The actual temperature distribution (see Figure 5(c)) was recorded using FLIR A300 thermal imaging camera and delineated by the temperature curve in Figure 5(e). The actual resultant temperature is in fair correspondence with the simulation result shown in Figure 5(d), making the proposed method feasible for accurate thermal control in practical applications.

5. Conclusions and further work

This research, for the first time, proposed an image based programming method for numerical thermal control of high-accuracy in scenarios of multi-source heating process in a wide range of industrial applications. The idea of using image processing liberates from time-consuming computation in finding the solution of the inverse problem of heat source estimation, which consequently enables numerically controlled heating process by allocating appropriate power states to heat suppliers in a step-wise manner. Excellent temperature uniformity and consistency with target temperature profile were achieved in both simulation and real heating tests.

The proposed method had been preliminarily validated. A more comprehensive heating model that would incorporate internal temperature distribution and heat radiation is being investigated for high temperature heating processes. Accurate calibration for complex parts with arbitrary shapes is also our next goal.

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