Composites: Part A 107 (2018) 10–20

Contents lists available at ScienceDirect

Composites: Part A

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

A multi-pattern compensation method to ensure even temperature in composite materials during microwave curing process

Jing Zhou [a], Yingguang Li [a,*], Nanya Li [a], Shuting Liu [a], Libing Cheng [a], Shaochun Sui [b], James Gao [c]

[a] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] Chengdu Aircraft Industrial (Group) Co., Ltd., Chengdu 610000, China
[c] Faculty of Engineering and Science, University of Greenwich, Chatham Maritime, Kent ME4 4TB, UK

ARTICLE INFO

Article history:
Received 27 July 2017
Received in revised form 9 November 2017
Accepted 16 December 2017
Available online 18 December 2017

Keywords:
A. Polymer-matrix composites (PMCs)
D. Process monitoring
E. Out of autoclave processing
E. Cure

ABSTRACT

Microwave curing technologies have many advantages in manufacturing fiber reinforced polymer composite materials used in aerospace products, compared with traditional autoclave curing technologies. However, the uneven electromagnetic field of microwave in the cavity of the curing chamber results in uneven temperature on the surface of composite laminates during curing, which has been a major obstacle in industrial applications worldwide. Existing methods attempted to solve the problem by the random superposition of uneven electromagnetic fields, but the results were still not satisfactory to meet the high quality requirements of aerospace parts. This paper reveals the one-to-one correspondence between heating patterns of composite parts and microwave curing system settings, and reports a new concept to solve this problem by continuously monitoring and compensating the uneven temperature distribution in real-time. Experimental results from both fiber optical fluorescence sensors and infrared thermal imagers showed significant improvement in temperature uniformity compared with existing methods.

1. Introduction

Fiber reinforced polymer composites with strong mechanical properties are increasingly used in aerospace products [1,2]. According to an investigation recently carried out in collaboration with Chinese Aircraft Industrial (Group) Co., around 98% composites used in the aerospace industry are fabricated using autoclave curing technologies, where the material is placed in a chamber and heated by the circulating airflow [3]. However, the technology has a number of problems which restrict further improvement of product quality and manufacturing efficiency [4]. For aerospace applications, the most important problem is the serious deformation of composites of large size with varying thickness, due to the large temperature gradient in the thickness direction. Other problems include long process cycles and high energy consumption [5]. For example, the annual output of the A350XWB will be 156 airplanes after 2018 [6], thus 312 wings need to be manufactured. For some composite parts, only the curing process may take up to 24 h with a maximum energy consumption of 4070 KW per hour for an autoclave of size Φ5m × 14 m [7,8], and the part deformation can be very severe [9]. This cannot meet the increasing demands for large quantity of high performance composites in modern aircrafts.

As an alternative to traditional autoclave curing technologies, microwave curing technologies can reduce curing time and energy consumption, and also reduce the temperature gradient within the composite material during curing. This is because microwaves can heat the whole volume of the material at the same time [10], thus greatly reducing the deformation of composite parts and improving the efficiency of the curing process [11]. To date, a lot of research work had been conducted on microwave curing of composites materials, including fundamental principles [12], curing kinetics [13], fiber/matrix interfaces [14], temperature gradients [15] and mechanical properties [16,17].

However, microwave curing technologies have not been widely applied in the aerospace industry because of the difficulties in ensuring an even temperature on the surface of composite laminates during curing [18,19]. The uneven temperature distribution is caused by the uneven resonance of the electromagnetic field in the cavity of microwave ovens [20]. Resonance can be considered as the effect where waves are incident from several directions at the same time. For any arbitrary point in the cavity, the separate wave fields incident from different directions interfere each other, i.e., they combine constructively and destructively in an alternating pattern, and form a standing wave during the superimposition

* Corresponding author.
E-mail address: liyingguang@nuaa.edu.cn (Y. Li).

https://doi.org/10.1016/j.compositesa.2017.12.017
1359-835X/

[21]. Over time 'hot spots' and 'cold spots' (relative to the hot spots), corresponding to antinodes and nodes of the standing wave will inevitably appear on the surface of composite materials, leading to the uneven in-plane temperature distribution. Because composite materials are basically laminated plate structures, the uneven temperature distribution on their surfaces has a significant impact on their curing performance, which can directly contribute to severe warpage and even local ablation or under-treatment.

In order to solve the uneven temperature problem, different ways had been attempted in the past which can be classified into four categories. The first one is focused on the design of the shape and size of the microwave cavity [22]. For example, the uniformity of the microwave field can be improved by increasing the size of the cavity. This is because the number of resonant modes (the distribution state of the electromagnetic field) within a microwave applicator increases rapidly as the size of the cavity increases, and sometimes the different resonant modes within the applicator are possible to have complementary effects. The second way is to use multiple microwave sources within the cavity since the resonant modes associated with different sources are able to overlap, which may further enhance the heating uniformity [23]. The third way is to generate a relative movement between the material and the electromagnetic field [24]. An example can be found in a microwave oven at home which is often equipped with a turning table that rotates the plate with food during operation. The purpose of the turning table is to reduce the effect of multiple hot spots by moving the object being heated through areas of high and low power fields alternately, so as to achieve uniformity in temperature of the food. The fourth way is to adopt variable-frequency microwave systems for materials processing, which can generate many different resonant modes by repeatedly applying different microwave frequencies thus achieving uniformity of power within the microwave cavity [25,26].

The above existing methods have, to different extents, improved the uniformity of microwave heating by random superposition of the uneven electromagnetic field within the microwave cavity. However, these methods cannot solve the problem from the scientific point of view, and the uneven temperature problem during microwave curing remains as a major challenge in the manufacturing of advanced composite materials [18,19]. This paper reveals the relationship between heating patterns of composite parts and microwave curing system settings. On this basis, a multi-pattern compensation method is proposed to achieve better uniformity of temperature on the surface of composite laminates during microwave curing. This method, through monitoring the uneven temperature distribution and applying appropriate compensating heating patterns in real-time, can significantly improve the homogeneity of the temperature field of composite parts during curing.

2. Idea of the multi-pattern compensation method

Through extensive experimental research, the authors found that there is a one-to-one correspondence between heating patterns (HPs) of composite parts and microwave curing system settings (MCSSs), as illustrated in Fig. 1. Corresponding theoretical analysis is presented in Section 5.1. Here, the HP is defined as the distribution law of the microwave power on the composite surface, which can be mathematically expressed as a matrix which contains the information of the microwave power and position.

$$\mathbf{HP} = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m1} & P_{m2} & \cdots & P_{mn} \end{bmatrix} \tag{1}$$

where P_{mn} is the microwave power at a certain point on the composite surface. The MCSS represents a couple of parameters regarding the resonant applicator, the microwave input and the composite part. Among them, parameters of the composite part (material, ply, shape, size and position) and the microwave equipment (shape, size, filling medium of the applicator, and frequency of the microwave input) can be regarded as constants and are difficult to be adjusted during curing, when a certain composite part and a certain industrial microwave oven (often with multiple microwave magnetrons) are selected. Fortunately, the position and the number of microwave inputs, as well as the power ratio between them can be easily controlled by adjusting the switches of various magnetrons of the oven as an electronic process. In this paper, the position and number of microwave inputs were used as the control strategy of the MCSS, and can be expressed mathematically as a vector.

$$\mathbf{MCSS} = [\,\delta_1, \quad \delta_2, \quad \cdots \quad \delta_l\,] \tag{2}$$

where δ_l is the switch state of the lth microwave input, which is a binary number and can be valued at 0 or 1. As mentioned above, the heating pattern of the composite can be controlled by adjusting the control strategy of the MCSS.

$$f(\mathbf{MCSS}) = \mathbf{HP} \tag{3}$$

According to the above analysis, the HP of the object being heated will not change as long as the related MCSS remains constant. Hence, when a part (or a new one of the same) is heated for a new run, the HPs collected beforehand can be used as a useful database to adjust its uneven temperature distribution. More specifically, when a certain temperature distribution is monitored, a HP with a complementary heating preference would be most beneficial to realize a uniform in-plane temperature distribution, especially when the high/low power sections of the HP are cold/hot spots for the current temperature distribution (see Fig. 2). This is the idea of the multi-pattern compensation method. It overcomes the limitation of random superposition principle in traditional method, and use complementary HPs to ensure even curing temperature during the whole curing process.

3. Implementation of the multi-pattern compensation method

A process control system is developed to implement the multi-pattern compensation method. As shown in Fig. 3, the structure of the system can be divided into two parts. One is aimed at improving the temperature uniformity of the composite part, and the other is to keep the average temperature following the setting temperature. It can be seen that before a composite part to be cured its database of HPs needs to be constructed. When the curing process is started, the temperature distribution of the part is monitored and analyzed in real time. If the maximum temperature difference exceeds a preset threshold ΔT_{max} (e.g., 6 °C), the HP selection controller will rapidly search the database for a HP that would alleviate the temperature heterogeneity the most. Once the HP is selected, the computer will rapidly adjust the switches of the magnetrons of the oven according to the related control strategy. Since composites are often cured by a fixed temperature process, the input power of these magnetrons also needs to be adjusted by a PID power controller to keep the average temperature following the setting temperature.

3.1. Strategy of HP database construction

As mentioned above, a database of HPs for a composite part needs to be set up before it is to be cured by microwave. This is accomplished by a preheating process of the part. The details are as follows.