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Numerical simulations and optimization of foam filled free-curved surface composite part

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Abstract

The purpose of this study is to predict the curing deformation of a foam-filled free-curved surface composite part and reduce the occurrence of curing deformation through process optimization. This research introduces a finite element simulation method and an optimization method for forming parameters for a foam-filled free-curved surface composite part. Meanwhile, sample manufacturing experiments and a comparative analysis between the simulation and actual objects were conducted. The results showed that finite element simulation analysis could effectively predict the curing deformation of the composite part. After the optimization simulation analysis of the molding process parameters, it was found that the curing deformation of the foam-filled free-curved surface composite part could be as small as 2.30 mm.

1. Introduction

Owing to the anisotropic property of composite materials and other factors, curing deformation was observed during the molding process of composite parts, which affected their accuracy [1]. To solve this problem, a simulation analysis of the forming process of composite materials was conducted to predict the curing deformation of the parts, and the parameters of the forming process were optimized to effectively improve the forming quality of those parts [2–5].

As the curing deformation of composite parts is a key factor that restricts the accuracy of their shape, prediction and simulation research on the curing deformation of composite parts is of great significance. Ameya et al considered the resin shrinkage rate, curing degree, thermal expansion direction coefficient, and other factors of composite laminates and used a curing kinetic model to describe the matrix behavior during the curing process. They successfully established a simulation model of the composite laminate, which accurately predicted the curing deformation of the composite material [6]. Using carbon fiber epoxy resin composites as the research object, Seong-Hwan Yoo et al considered the phase change of the resin and conducted finite element simulation analysis on the hot-press molding process of the composites, which successfully established the curing and deformation model of carbon fiber epoxy composites and verified the correctness of the model [7]. Liu et al established a simplified constitutive model of the resin curing process considering stress relaxation, conducted a curing simulation analysis on L-shaped composite parts, and quantitatively discussed the influence mechanisms of various factors [8]. At present, curing simulation research of composite materials mostly focuses on theoretical models, and further analysis of the curing simulation of actual parts or parts with complex shapes is needed. Additionally, it is necessary to consider the deformation prediction accuracy and calculate the speed of the finite element simulation model to achieve better practicality.

Many researchers have conducted related studies on the forming simulation and process optimization of composite materials. Anita Zade et al carried out a numerical simulation of the empirical curing rate model of the
non-isothermal resin transfer molding curing process cycle and discussed the influence of thickness on curing time and curing deformation [9]. Olivier and El Sawi conducted a simulation study on composite laminates based on a curing kinetic model and found that a lower curing temperature produced less curing deformation, but the curing process lasted longer [10]. Bogetti and Gillespie Jr combined the one-dimensional curing simulation analysis with the incremental laminate theoretical model [11]. Their study showed that the heating rate affected the curing sequence of the part in the direction of thickness, and there should be a specific heating rate that could theoretically cure the inside and outside of the part at the same time. Nawab et al. established a curing simulation model for glass fiber vinyl ester resin composites, analyzed the effect of pressure on the chemical shrinkage rate, and found that applying higher pressure produced greater chemical shrinkage [12]. Lian reviewed the simulation model of composite material curing deformation and clarified that chemical shrinkage was one of the main mechanisms leading to curing deformation and that pressure affected the chemical shrinkage, thus affecting the curing deformation [13]. Baran and Joven established a simulation model of the interaction between the mold and part during the molding process and clarified that the interaction between the mold and part was the external source of curing deformation [14, 15]. They also introduced the influence mechanism of the mold on the molding of the composite materials. Mainly based on qualitative analysis of the influence mechanism of a single factor, the above-mentioned studies, however, have not discussed the superposition of multiple influence factors, which is of little help in the optimization of the molding process of specific composite parts.

In the field of aviation manufacturing, especially in the manufacturing of helicopter rotor, in order to make the external surface of rotor blade and ensure its light and strength, the part structure of rotor is more complex than the analyzed existing composite parts. People usually use the bearing beam to improve the internal strength of the parts, and fill them with honeycomb foam, together with the composite skin to maintain the accuracy of the external surface and reduce the weight of the parts [16–19]. As a result, complex parts further increase the uncertainty of curing of composite parts. Some experts and scholars have done some researches on composite materials with honeycomb foam, including Sebaey established a model of the relationship between foam and skin during the molding process and found that foam filling increased the energy absorption capacity of composite parts and improved their structural integrity [20]. Shih-Yu Huang et al. found that foam filling was conducive to an increase in the elongation of composite materials and effectively improved the impact resistance of composite materials [21]. However, their research is mainly focused on the effect of the increase of honeycomb foam on the performance of composite parts, but little research has been done on the effect of honeycomb foam on curing deformation of composite parts. In the molding process of parts, accurate analysis of the deformation mechanism of foam filling and the interaction between foam and skin are of great significance to the molding process of such parts.

The originality and novelty of this research lies in its study of foam-filled free-curved surface composite parts. This paper presented related mathematical models and finite element simulation models for the formation process of composite parts, analyzed the effect of honeycomb foam filling on the surface deformation during curing, and verified the validity of the simulation model through digital measurement experiments. Further more, based on the above simulation model, the forming process parameters of the composite part were optimized and the optimal process parameters were obtained.

2. Theoretical analysis

The object of this study was a foam-filled free-curved surface composite part with a span length of 800 mm and a chord length of 580 mm. The interior of the composite part was a carbon fiber composite D-beam and

Figure 1. Composite part with free-curved surface.
honeycomb foam material, and the exterior was wrapped with a carbon fiber composite skin. When the D-beam and honeycomb foam were molded and bonded as components with the skin, the skin was not yet formed. Therefore, in this study, the molding process of the carbon fiber composite skin with a D-beam and honeycomb foam was shown in figure 1. This study comprehensively considered factors including raw materials of parts, process parameters, and molds, and then established thermochemical, non-mechanical contingency, and interaction models of foam and skin to accurately describe the forming process of composite parts.

2.1. Composite viscoelastic constitutive equation

The composite material was composed of reinforcing fibers and resins. During the heating and curing process, the properties of the reinforcing fiber hardly change, showing a linear elastic behavior, whereas the material properties of the resin gradually change under the action of temperature, showing a viscoelastic behavior. Thus, a composite material can be expressed as a combination of an ideal linear elastomer and an ideal viscoelastic body.

According to the generalized Maxwell model, the stress of the resin material under a constant strain \( \varepsilon_0 \) at time \( t \) can be expressed as follows:

\[
\sigma(t) = \varepsilon_0 \left[ E^\infty + \sum_{m=1}^{M} W_m (E^0 - E^\infty) \exp \left( \frac{t}{\tau_m} \right) \right]
\]

where \( E^\infty \) is the elastic modulus of the material in the rubbery state or its elastic modulus in the initial stage, \( W_m \) represents the weight coefficient of the mth branch of the generalized Maxwell model, \( E^0 \) is the material’s elastic modulus in the glassy state or its elastic modulus in the initial stage, and \( \tau_m \) represents the relaxation time of the mth branch element of the generalized Maxwell model, both of which are listed in table 1.

According to the Boltzmann superposition principle, the total stress generated by a resin material is regarded as the sum of the effects of each strain on the resin material. Thus, the constitutive equation of the resin material can be expressed as [22–27]:

\[
\sigma(t) = \int_0^t E(t - t') \frac{\partial \varepsilon(t')}{\partial t'} dt'
\]

where \( E(t) \) is the elastic modulus at time \( t \). According to the time-temperature equivalence principle, the elastic modulus of the resin material under a certain higher temperature \( T_1 \) and shorter time \( t_1 \) is equal to the elastic modulus under another lower temperature \( T_2 \) and shorter time \( t_2 \), which can be expressed as

\[
E(T_1, t_1) = E(T_2, t/t_1)
\]

where, \( a_T \) is the conversion factor. The relationship between the stress and strain of the resin material under any temperature curve and time condition can be obtained by substituting equations 3 into 2.

\[
\sigma(t) = \int_0^t E(\xi(t) - \xi'(t')) \frac{\partial \varepsilon(t')}{\partial t'} dt'
\]

where \( \xi(t) \) and \( \xi'(t') \) are the reduction times and are related to \( a_T \) as follows:

\[
\xi(t) = \int_0^t \frac{1}{a_T} dt
\]
By simplifying the composite material into a single-layer board structure, the unidirectional tape prepreg can be described as an orthotropic material composed of fibers and resins. The composite constitutive equation can be expressed as \[ \sigma_i = \left[\begin{array}{cccc}
\sigma_{11} & C_{12} & C_{13} & 0 \\
C_{21} & \sigma_{22} & C_{23} & 0 \\
C_{31} & C_{32} & \sigma_{33} & 0 \\
0 & 0 & 0 & \sigma_{44}
\end{array}\right] \left[\begin{array}{c}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4
\end{array}\right] + \left[\begin{array}{c}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4
\end{array}\right] \left[\begin{array}{c}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4
\end{array}\right] \cdot \left[\begin{array}{c}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4
\end{array}\right]
\] (8)

\( \sigma_i \) is the normal stress, \( \varepsilon_1 \) represents the normal strain in the \( i \) direction of the coordinate system of the material, and \( C_{ij} \) is the stiffness component of the material (in tensor form).

\[
\begin{align*}
C_{11} &= \frac{1 - \nu_{13} \nu_{32}}{E_2 E_3 S} \\
C_{12} &= \frac{\nu_{21} + \nu_{23} \nu_{31}}{E_2 E_3 S} \\
C_{13} &= \frac{\nu_{11} + \nu_{13} \nu_{32}}{E_2 E_3 S} \\
C_{22} &= \frac{1 - \nu_{21} \nu_{13}}{E_1 E_3 S} \\
C_{23} &= \frac{\nu_{22} + \nu_{12} \nu_{31}}{E_1 E_3 S} \\
C_{33} &= \frac{1 - \nu_{12} \nu_{21}}{E_1 E_2 S} \\
C_{14} &= G_{23} \\
C_{55} &= G_{31} \\
C_{66} &= G_{12} \\
S &= \frac{1 - \nu_{12} \nu_{21} - \nu_{22} \nu_{32} - \nu_{13} \nu_{31} - 2 \nu_{12} \nu_{31} \nu_{13}}{E_1 E_2 E_3}
\end{align*}
\] (9)

\( E_i \) is the elastic modulus in the \( i \) direction of the coordinate system of the material, \( \nu_{ij} \) is the Poisson’s ratio in the \( i \) and \( j \) directions of the coordinate system of the material, \( G_{ij} \) is the shear modulus in the \( i \) and \( j \) directions of the coordinate system of the material.

Its relaxation stiffness can be represented by the material stiffness matrix [29]:

\[
C_{ij}(\xi) = C_{ij}^\infty + (C_{ij}^0 - C_{ij}^\infty) \sum_m W_m \exp \left( -\frac{\xi}{\tau_m} \right)
\] (10)

\[
\tau_m(a) = 10^{[\log(a) \cdot (f(a) - (a - a_1) \cdot \log(\lambda_m))]}
\] (11)

\[
f(a) = 9.1347a^2 + 0.6089a - 9.3694
\] (12)

\[
\lambda_m = \frac{10^{a_9}}{\tau_m(a_T)}
\] (13)

\[
a_T = 10^{[-a_1 \cdot \exp \left( \frac{1}{a_7} \right) - a_2] \cdot [T - T_i]}
\] (14)

\[
\Delta \xi^+ = \int_t^{t+\Delta t} \frac{d\xi}{d\tau} = \frac{\Delta t}{a_T}
\] (15)

\( a \) is the curing degree of the composite material and \( T_i \) is the corresponding reference temperature. \( C_{ij}(\xi) \), \( C_{ij}^\infty \) is the material’s stiffness component (tensor form) at reduced time \( \xi \), \( C_{ij}^\infty \) is the stiffness component of the rubber state or the stiffness component (tensor form) in its equilibrium stage, \( C_{ij}^0 \) is the material’s stiffness component of the glass state or the stiffness component (tensor form) in the initial stage. Assuming that the composite material is a simple thermal rheological material, we have

\[
C_{ij}^\infty = rC_{ij} \quad C_{ij} = (1 - r)C_{ij}
\] (16)
The stress increment of the material can be expressed as:

$$
\Delta \sigma_i^{t+\Delta t} = \sigma_i^{t+\Delta t} - \sigma_i^t
= \int_0^{\xi} C_{ij} \sum_m W_m \exp\left( -\frac{\xi_j^t - \xi_j^0}{\tau_m} \right) \left( \exp\left( -\frac{\Delta \xi_j^t}{\tau_m} \right) - 1 \right) \frac{\partial \varepsilon_{ij}^{\text{eff}}}{\partial \xi} \, d\xi
+ \int_{\xi}^{\xi+\Delta \xi} \left[ C_{ij}^0 + C_{ij} \sum_m W_m \exp\left( -\frac{\xi_j^t - \xi_j^0}{\tau_m} \right) \right] \frac{\partial \varepsilon_{ij}^{\text{eff}}}{\partial \xi} \, d\xi
$$

(17)

where $\varepsilon_{ij}^{\text{eff}}$ is the effective strain vector, which is a function of the temperature and degree of curing. Assuming that the strain varies linearly within a unit time increment and that the temperature and degree of cure variables are negligible, the material stress-strain relationship can be expressed as

$$
\Delta \sigma_i^{t+\Delta t} = C_{ij} \Delta \varepsilon_{ij}^{t+\Delta t} + \sum_m \exp\left( -\frac{\Delta \xi_j^t}{\tau_m} \right) - 1 \right) S_i(t)
$$

(18)

$$
S_i(t) = \left[ \exp\left( -\frac{\Delta \xi_j^t}{\tau_m} \right) S_i(t - \Delta t) + C_{ij} \sum_m W_m \frac{\tau_m}{\tau_m} \frac{D_i^t}{\Delta t} \left[ 1 - \exp\left( -\frac{\Delta \xi_j^t}{\tau_m} \right) \right] \right)
$$

(19)

2.2. Thermochemical model

The thermochemical model is mainly used to describe the relationship between the temperature of the composite material $T$, thermal conductivity $\lambda$, curing degree $\alpha$, and curing exotherm $Q$ during the curing process of the composite skin. The temperature change of the composite material is mainly affected by two factors: heat transfer by an external heat source and internal curing exotherm of the composite material. Hence, the heat-transfer model of the composite skin can be described by the following equation [30]:

$$
\frac{\rho}{\rho_i} \frac{\partial^2 T}{\partial x^2} + \lambda_x \frac{\partial^2 T}{\partial y^2} + \lambda_y \frac{\partial^2 T}{\partial z^2} + Q = \frac{\partial C}{\partial t}
$$

(20)

where $\rho$ is the density of the composite; $C$ represents the heat capacity of the composite; $\lambda_x$, $\lambda_y$, and $\lambda_z$ are the coefficients of thermal conductivity of the composite in the $x$, $y$, and $z$ directions, respectively. In the composite simulation model, the $x$-direction is the spanwise direction, the $y$ direction is the outward direction perpendicular to the skin surface, the $z$ direction is perpendicular to the $xy$ plane, $T$ represents the temperature of the composite node, $t$ is the time, $Q$ is the thermal generation rate. The expression is:

$$
Q = \rho_i (1 - V_f) \rho_i \frac{dT}{dt}
$$

(21)

where $\rho_i$ is the density of the resin; $V_f$ is the fiber volume fraction; $H_i$ is the total heat released from the curing reaction of the unit mass resin; $\alpha$ is the curing degree, $d\alpha/dt$ is the curing rate. Because different resin materials correspond to different curing reaction rates and curing exotherms, some of the parameters in the expression are different.

According to phenomenology from the perspective of engineering applications, the reaction rate $d\alpha/dt$ is a function of temperature ($T$) and curing degree ($\alpha$), and its basic kinetic equation is as follows:

$$
\frac{d\alpha}{dt} = K_i f(\alpha)
$$

(22)

According to the relationship characteristics of the material’s heat flow, time, and temperature, the relationship between the curing rate of the corresponding material and the temperature ($T$) and curing degree ($\alpha$). Taking the matrix material in the 3238 A/C-1F-052 prepreg as an example, it can be expressed as:

$$
\frac{d\alpha}{dt} = \begin{cases} (K_i + K_2 \alpha)(1 - \alpha)(0.47 - \alpha), & \alpha \leq 0.3 \\ K_2(1 - \alpha), & \alpha \geq 0.3 \end{cases}
$$

(23)

where $K_i$ corresponds to the Arrhenius equation, which can be expressed as follows:

$$
K_i = A_i \exp \left( -\frac{\Delta E_i}{RT} \right), \quad i = 1, 2, 3
$$

(24)

where $K_i$ is the reaction rate constant of the self-catalysis model, $A_i$ is the frequency factor for the self-catalysis model, $\Delta E_i$ is the activation energy of the self-catalysis model, $R$ is the ideal gas constant.
Based on the above model, changes in the curing degree and heat with time and temperature during the curing process of the composite material can be effectively simulated.

2.3. Non-mechanical strain model

The nonmechanical strain model is mainly used to describe the thermal strain and curing shrinkage strain during skin formation. The overall strain of the composite during its heating and curing processes consists of mechanical and non-mechanical strains, constituting the thermal strain $\varepsilon_{th}$ and chemical shrinkage strain $\varepsilon_{sh}$ constitute. The thermal strain $\varepsilon_{th}$ is caused by the change in temperature, and the chemical shrinkage strain $\varepsilon_{sh}$ results from the curing shrinkage of the resin matrix. Predicting the non-mechanical strain of composite materials through numerical simulations is the basis for accurately forecasting the curing deformation trends of these materials.

The thermal expansion coefficient $\alpha_r$, which is influenced by the curing degree and temperature of the resin, can be expressed as the increase in the thermal strain of the resin $\Delta \varepsilon_{th}$ under a unit temperature difference $\Delta T$:

$$\Delta \varepsilon_{th} = \alpha_r \Delta T$$

If one of the three orthogonal symmetry planes of the orthotropic materials is an isotropic plane, the material is transversely isotropic, and the mechanical properties of the materials in all directions of the isotropic plane are the same. The plane perpendicular to the fiber direction of the unidirectional laminated composites is an isotropic plane, and the elastic properties of each point in the plane are the same in all directions. Therefore, unidirectional fiber composites can be considered as transversely isotropic materials, and the composite skin can be regarded as a laminated plate composed of multilayer single-layer plates. The thermal expansion coefficient of the composite can be predicted using the self-consistent field micromechanics model (SCFM) as follows:

$$\alpha_1 = \frac{\alpha_{1f} E_{1f} V_f + \alpha_{2f} E_{1f}(1 - V_f)}{E_{1f} V_f + E_r (1 - V_f)}$$

$$\alpha_2 = \alpha_3 = \alpha_{2f} + V_{12f} \alpha_{1f} V_f + (\alpha_r + V_r \alpha_r) (1 - V_f)$$

$$- \left[ V_{12f} V_f + V_r (1 - V_f) \right] \alpha_1$$

where $\alpha_{1f}$, $\alpha_{2f}$ are the thermal expansion coefficients of the fiber in the parallel and perpendicular directions of the fiber; $\alpha_r$ is the thermal expansion coefficient of the resin; $E_{1f}$ is the elastic modulus of the fiber in the parallel direction of the fiber; $E_r$ represents the elastic modulus of the resin; $\nu_l$ is the Poisson’s ratio of the resin; $\nu_{12f}$ represents the longitudinal and transverse Poisson’s ratio of the fiber; and $V_f$ is the volume content percentage of the fiber.

By calculating the thermal expansion coefficient of the composite, its thermal strain increment was calculated using the following formula:

$$\Delta \varepsilon_{th} = \alpha_1 \Delta T$$

$$\Delta \varepsilon_{2h} = \Delta \varepsilon_{sh} = \alpha_2 \Delta T = \alpha_3 \Delta T$$

Similarly, the curing shrinkage strains $\varepsilon_{1h}$ and $\varepsilon_{2h}$ in the principal direction of the material can be derived.

Based on the above model, the nonmechanical strain of the composite skin in all directions during curing can be effectively simulated.

2.4. Analysis of foam-skin interaction

When foam filled composite parts are cured, the residual stresses and strains will be affected by honeycomb foam in addition to anisotropic thermal expansion, shrinkage and mold. The foam mainly produces two kinds of stresses on the part. The first one is that when the skin is perpendicular to the honeycomb foam, the honeycomb foam is heated and expanded to produce compressive stresses on the skin contact surface. The other kind of
stress is that when the skin is parallel to the honeycomb foam, due to the difference of the thermal expansion coefficient between the composite material and honeycomb sandwich, the shear stresses of the composite skin contact surface is caused, which is shown in figure 2.

In the process of skin forming, the thickness of the skin parts is almost negligible compared to the thickness of the honeycomb foam. Therefore, the pressure of interaction between skin and honeycomb foam can be expressed as:

\[ P = K_\text{foam} \alpha_\text{foam} (T - T_0) \]  

(30)

In the formula, \( K_\text{foam} \) represents the bulk modulus of the foam, \( \alpha_\text{foam} \) indicates the thermal expansion coefficient of the foam, \( T \) represent the current temperature and \( T_0 \) represent initial temperature.

The shear stress can be fitted by the laminate model, in which the thermal expansion coefficient of the composite skin has been calculated in section 2.3, then the shear stress can be expressed as:

\[ \sigma_{\text{fs}} = E_s (\alpha_s - \alpha_f)(T - T_0) \]  

(31)

In the formula, \( E_s \) is the elastic modulus of the composite, \( \alpha_s - \alpha_f \) represents a difference in thermal expansion coefficient between composite skin and honeycomb foam filled composites, and \( T - T_0 \) represents temperature change.

The overall thermal expansion coefficient of honeycomb foam filled parts can be expressed by formula:

\[ \alpha_s = \frac{A_s E_s \alpha_s + A_\text{foam} E_\text{foam} \alpha_\text{foam}}{A_s E_s + A_\text{foam} E_\text{foam}} \]  

(32)

Where, \( A_s \) is the cross-sectional area of the skin, \( \alpha_s \) is the thermal expansion coefficient of composite materials, similarly, \( A_\text{foam}, E_\text{foam}, \alpha_\text{foam} \) represent the corresponding coefficients of foam.

It can be seen from the formula that when the thickness of honeycomb foam is much larger than that of the composite skin, the thermal expansion coefficient of the whole part is approximately equal to the thermal expansion coefficient of the honeycomb foam. Therefore

\[ \sigma_{\text{fs}} = E_s (\alpha_\text{foam} - \alpha_f)(T - T_0) \]  

(33)

The thermal strain of the foam can be expressed as:

\[ \Delta \varepsilon = \alpha_\text{foam} \Delta T \]  

(34)

Where, \( \Delta T \) is the temperature difference.

2.5. Non-mechanical strain model Application of mathematical-physical model

The curing kinetic constants and mechanical and non-mechanical properties of the composite defined in the mathematical model mentioned above are listed in tables 2–4.

To accurately describe the above mathematical model and substitute it into the calculation process of the finite element simulation model, five simulation subroutines were written in this study: DISP, HETVAL, USDFLD, UMAT, and UEXPAN.

The external temperature load curve is defined by the DISP subroutine and is represented by parameter U(1). The USDFLD subroutine defines the curing degree of the composite material through the STATEV(1)

### Table 2. Weighting coefficient and relaxation of resin.

| Parameters | Value |
|------------|-------|
| \( \rho_f / \text{t/mm}^3 \) | \( 1.76 \times 10^{-9} \) |
| \( C_c / \text{ml}/(\text{t-K}) \) | \( 7.942 \times 108 \) |
| \( \lambda_s / \text{mW}/(\text{mm-K}) \) | 10.45 |
| \( \lambda_h / \text{mW}/(\text{mm-K}) \) | 0.7959 |
| \( A / \text{t/mm}^3 \) | \( 1.2 \times 10^{-9} \) |
| \( V_f \) | 50% |
| \( H_s / (\text{l-kg}^{-1}) \) | 473600 |
| \( A_t / (\text{min}^{-1}) \) | \( 2.101 \times 109 \) |
| \( A_s / (\text{min}^{-1}) \) | \( -2.014 \times 109 \) |
| \( A_z / (\text{min}^{-1}) \) | \( 1.96 \times 105 \) |
| \( \Delta E_f / (\text{J-mol}^{-1}) \) | \( 8.07 \times 104 \) |
| \( \Delta E_s / (\text{J-mol}^{-1}) \) | \( 7.78 \times 104 \) |
| \( \Delta E_s / (\text{J-mol}^{-1}) \) | \( 5.66 \times 104 \) |
| \( R / (\text{J/(mol-K^{-1})}) \) | 8.3143 |
variable, whose value varies with the node temperature and time. STATEV(1) will be called cyclically in other subroutines. The internal exothermic heat during the curing process of the composite material is defined in the HETVAL subroutine, which mainly defines FLUX. The relevant parameter of STATEV(1) is associated with the curing degree variable, which is used to represent the curing exothermic heat of the composite material per unit volume. In the UMAT subprogram, the stiffness matrix of the composite material is defined through DDSDDE, which is used to characterize the relationship between the stress and strain of each node of the composite material under the conditions of current temperature, time, and curing degree. The stiffness matrix of the material is related to the temperature, time, and degree of cure parameters corresponding to the node. Finally, the thermal expansion and curing shrinkage strains of the composites were defined in the UEXPAN subroutine using EXPAN parameters.

The calling logic of the subroutine is shown in figure 3, where a change in the incremental step of the simulation model drives the temperature change in the DISP subroutine. The temperature and time changes

---

**Table 3. Mechanical properties of composite.**

| Parameters | Value |
|------------|-------|
| $E_1 \, \text{GPa}$ | 126 |
| $E_2 = E_3 \, \text{GPa}$ | 8.3 |
| $G_{12} = G_{13} \, \text{GPa}$ | 4.1 |
| $G_{23} \, \text{GPa}$ | 2.8 |
| $\alpha_1 / \degree \text{C}^{-1}$ | $0.5 \times 10^{-6}$ |
| $\alpha_2 = \alpha_3 / \degree \text{C}^{-1}$ | $35.3 \times 10^{-6}$ |
| $\alpha_{c1} / \degree \text{C}^{-1}$ | $167 \times 10^{-6}$ |
| $\alpha_{c2} = \alpha_{c3} / \degree \text{C}^{-1}$ | $8810 \times 10^{-6}$ |

**Table 4. Material parameters of composite skin in non-mechanical strain model.**

| Parameters | Value |
|------------|-------|
| $E_{1f} \, \text{MPa}$ | 29400 |
| $E_r \, \text{MPa}$ | 1000 |
| $\alpha_{1f} \, \degree \text{C}^{-1}$ | $-9 \times 10^{-7}$ |
| $\alpha_{2f} \, \degree \text{C}^{-1}$ | $7.2 \times 10^{-6}$ |
| $\nu_{12f}$ | 0.35 |
| $\alpha_s \, \degree \text{C}^{-1}$ | $5.76 \times 10^{-5}$ |
| $\nu_{1}$ | 0.38 |

---

Figure 3. The calling sequence of ABAQUS subroutines.
lead to corresponding differences in the temperature, curing degree, heat release, stress, strain, and non-mechanical properties of each node and outputs to the simulation model. After the calculation results converge in this incremental step, the next incremental cloth is entered into the next incremental cloth.

3. Sample manufacturing and analysis of finite element simulation

3.1. Analysis of research object and sample manufacturing

The free-form surface composite parts filled with foam are made up of three parts, D-beam structure, honeycomb foam and external composite skin. The D-beam and honeycomb foam are made separately and connected by glue. After ensuring the connected parts meet the accuracy requirement, the composite skin is laid on them through adhesive bonding. The forming process is shown in figure 4. Because the D-beam and honeycomb foam inside the composite material have reached the accuracy requirement of the shape surface, the influence of manufacturing error and deformation of them on the composite skin is not considered in the simulation analysis. In the analysis, the D-beam and honeycomb foam are used as the ideal internal structure. Therefore, we will only consider the effect of D-beam and honeycomb foam on the skin of composite materials due to thermal expansion and other factors when the composite skin is cured.

The foam-filled free-curved surface composite parts studied in this study have a span-wise length of 800 mm and a chord-wise length of 580 mm, which is composed of three parts: composite skins, D-beams, and cellular foam structures, as shown below. The skin material is a 3238 A C−1F−3052 thermosetting composite material prepreg. The D-shaped beam is made of T800 grade carbon fiber material with a section width of 232 mm and a section height of 66 mm. Meanwhile, the layup angles of the skin and D-shaped beam are both [0°/0°/45°/0°], where the direction of 0°is . The honeycomb foam, which is mainly composed of A52 foam, is mostly used to fill the internal structure of the part and is bonded to the D-beam and the skin by gluing.

Before forming the composite skin, a D-beam and a cellular foam were formed. Subsequently, under the combined action of the mold, D-beam, cellular foam, and external temperature and pressure, the composite skin was cured and formed. Through the method of compression molding, the free-curved surface composite parts were molded with forming molds, including two parts: upper and lower molds, whose specific structures were shown in figure 5. The temperature curve of the molding process was designed using a two-stage heating
and pressurizing method. Figure 6 shows the temperature and pressure curves of the molding process. First, a pressure of 6 MPa was put to the mold at a pressurization speed of 0.3 MPa min$^{-1}$ to complete the initial mold closing, and maintained at a pressure of 6 MPa for 60 min. Then a pressure of 12 MPa was put to the mold at a pressurization speed of 0.3 MPa min$^{-1}$, and maintained until the part was completely cured, and then the pressure and mold were released. While the mold was pressurized, the mold was heated from room temperature to 70 °C at a heating rate of 1.5 °C min$^{-1}$. This temperature was maintained for 30 min so that the mold and the interior and exterior of the parts were evenly heated. Then the temperature was increased to 125 °C at a temperature of 1.5 °C min$^{-1}$ and maintained for 135 min to fully solidify the part, followed by cooling. After the parts were cured, they were demolded and placed on a wooden frame where they deformed and rebounded at room temperature. The free-curved surface composite part was formed under the aforementioned forming process, as shown in figure 7.

3.2. Establishment of finite element simulation model

Combined with the user subroutine, this study analyzed the curing deformation of composite materials using the finite element analysis software ABAQUS. The heat transfer, degree of cure change, and stress-strain relationship between the mold, part, and material inside the part under the action of temperature and pressure were considered, and the corresponding material parameters, including the change in the curing degree of each component of the part during the heating process, the change in each material property with the curing degree, and the internal heating of the material during curing were defined in the simulation process.

In the simulation model, this study used the material model mentioned in sections 1.1 and 1.2, for the composite skin of 3238 A/CF3052 material and combined it with user subroutines to simulate the curing deformation of the composite material. The material properties of the D-beam, foam, and mold are listed in table 5.
According to the forming process of free-curved surface composite parts, a simulation model was established, where there were a total of 143107 elements with the element type being C3D4 tetrahedron element. The boundary conditions and loads shown in Figure 8 were defined in the simulation model.

In the curing deformation process, the main loads include temperature and pressure loads. The temperature load gradually transferred heat to the composite parts by setting the mold temperature change curve. The pressure load acted directly on the upper mold surface of the composite part according to the pressure curve, and the pressure direction was vertically downward. In solidification deformation, the boundary conditions are mainly used to define the contact conditions between the mold-part and the internal parts of the part, and to limit the movement of the mold. Under the definition of the simulation model, the lower surface of the mold is completely fixed; the interaction between the mold and the outer surface of the part skin is set to surface contact, and the interaction between the inner surface of the skin and the honeycomb foam and D-beam is set to bonding (Tie), the interaction between the D-beam and the cellular foam is also set to bond (Tie).

During the deformation and rebound processes, the interaction relationship between the part and various structures inside the part remained unchanged. The interaction between the outer surface of the skin and the shelf was set to surface contact, and overall gravity was applied.

The surface contact considers penalty friction and heat transfer with a friction coefficient of 0.35 and a thermal conductivity coefficient of 40 mW/(mm·K). The external temperature gradually changes according to the temperature change curve when the part is formed, and the heat is transferred to the composite part through the mold so that the part gradually heats up and solidifies.

### 3.3. Analysis of research object and sample manufacturing

Through finite element simulation, this study obtained the simulation result of the Invar steel solid mold. Figures 9 and 10 show the stress and strain distributions of the composite part after curing.

By comparing the skin deformation data model with the scanning model of the test piece, which was obtained by three-dimensional scanning processing of the actual processed test piece (as shown in figure 11), it can be verified that the molding conditions of the test piece were consistent with the simulated molding conditions of the Invar steel solid mold.

Using the Geomagic Control software, the simulation deformation springback results can be compared with the actual part scanning digital model, as shown in figure 12.

Most of the errors between the simulation deformation and springback results and the actual part scanning digital model were less than 1 mm, which appear green in the comparison results. Some of the simulated deformation and springback results are inside the scanning digital model of the actual part, and the error is about 1 mm–1.5 mm, which appear blue in the comparison results. A very small part of the simulated deformation and springback results was outside the scanning digital model of the actual part, and the error was less than 1.5 mm.

| Parameters                  | Value (3 kinds of materials) |
|-----------------------------|-------------------------------|
|                            | T800 carbon fiber | Cellular foam | Invar steel |
| Density $\rho$/t mm$^3$     | $1.81 \times 10^{-9}$ | $5.2 \times 10^{-11}$ | $8.1 \times 10^{-9}$ |
| Thermal conductivity /mW/(mm·K) | 35.01      | 0.031          | 11          |
| Specific heat Cm/ml/(t·K)   | $7.534 \times 10^8$ | $4.2 \times 10^9$ | $5.15 \times 10^8$ |
| Elasticity (Engineering constant or $a_\alpha$°C$^{-1}$) | $-0.5610 \times 10^{-8}$ | $3.70 \times 10^{-5}$ | $1.6 \times 10^{-6}$ |
| Elasticity (Young’s modulus/kPa-Poisson’s ratio) | /              | /              | 123000/0.22  |

Table 5. Material properties.
which appeared yellow in the comparison results. It can be observed from the comparison that the simulation
deformation springback trend is basically the same as the actual part deformation springback trend, and the
comparison results have a high degree of coincidence, which verifies the correctness of the simulation results.

The simulation results are compared with the designed numerical simulations to obtain the deformation of
the part surface, as shown in the figure 13. It can be seen that in addition to the above green error band with an
error of less than 1 mm and the yellow band with an error between 1 mm to 1.5 mm, there is also the dark yellow
band with an error between 1.5 mm to 2 mm. The yellow band indicates that the simulation results in these areas
are within the range of the designed numerical simulations, that is, the parts rebound to the internal direction.
The deformation and rebounding processes of parts mainly appear on the part with small curvature of the

![Figure 9. Stress distribution of part curing: (a) the upper surface of part; (b) the lower surface of part.](image)

![Figure 10. Displacement distribution of part curing: (a) the upper surface of part; (b) the lower surface of part.](image)

![Figure 11. Scanning model: (a) Actual manufactured specimen; (b) Scanning specimen with 3D scanner; (c) 3D points obtained after scanning; (d) Scanning model obtained after processing 3D points.](image)
leading edge and the part with large curvature of the trailing edge, showing the trend of inward rebounds. And the simulation results show that the error area of the large curvature of the trailing edge is worse, which indicates that the rebounding is slightly larger than the actual situation. In contrast, the inward rebounding of the small curvature of the leading edge is smaller than the actual situation.

Through in-depth analysis of the rebounding processes of parts, it is found that the rebounding trend of foam filled free-curved surface composite parts is contrary to the previous research results. Those previous studies are aimed at the rebounding processes of L-shaped, Ω-shaped and V-shaped composite parts in simulation molds. In depth analysis of the distribution of parts and foam in the curing process, it is found that during the heating and curing process, the foam is heated and expanded. However, due to the limitation of the mold and the skin, the foam cannot expand along the direction perpendicular to the surface of the skin, so it can only expand spanwise. In this process, it can be observed that the parts produce obvious compressive stress and spanwise tensile stress, as shown in the figure 14.

As the temperature drops, the foam shrinks in the direction perpendicular to the surface of the skin, and it also shrinks spanwise, thus driving the skin to rebound inwards, resulting in the rebounding of the free-curved surface composite parts. This shows that the shrinkage of the foam has a great influence on the curing and deformation of the part.

Figure 12. Distortion comparison between simulation model and scanning model: (a) deformation comparison on upper surface; (b) deformation comparison on lower surface.

Figure 13. Distortion comparison between simulation model and design model: (a) deformation comparison on upper surface; (b) deformation comparison on lower surface.
4. Analysis of simulation optimization

During the forming process of free-curved composite parts, temperature and pressure have an important influence on the curing distortion of the parts. In addition, the temperature and pressure are coupled, and there is a superimposed synergistic effect between them. This study analyzed the effects of curing plateau temperature, heating rate, demolding temperature, and curing pressure on the curing deformation of parts during the molding process. In addition, this study explored the optimal molding process parameters for free-curved surface composite parts.

4.1. Molding process parameters of optimal result under univariate conditions

To determine the optimal molding process parameters of composite parts with a free-curved surface under the condition of multi-factor mutual coupling, this study uses the molding parameters of the sample to simulate part forming under univariate conditions to initially determine the optimal molding parameters. In this study, a simulation test of part forming under single-factor conditions, as shown in table 6, was designed.
Figure 15 shows the simulation results of the curing deformation of the free-curved surface composite parts under univariate conditions. The maximum deformation in the results was a negative deviation from the part surface. According to the results, it can be found that when the curing temperature of the part was too high, the maximum deformation increased, and when the curing temperature was too low, the part was incompletely cured and the maximum deformation increased. The optimal curing and forming temperature of the part under single factor conditions was 125 °C. As for the heating rate, when the heating rate was less than 1.404 °C min⁻¹, the accuracy was reduced due to insufficient curing; and when the heating rate was greater than 1.65 °C min⁻¹, the unevenness of temperature increased resulting in an increase in uneven deformation, thereby increasing the maximum amount of deformation as a whole. Experiments showed that the appropriate heating rate was approximately 1.486 °C min⁻¹, and increasing or decreasing the heating rate will lead to a larger curing deformation of the parts.

For the demolding temperature, the lower the demolding temperature of the part, the better the molding quality, which conforms to the theoretical analysis. When the demolding temperature was appropriately reduced, the plasticity of the part increased. After the mold constraint was released, spring-back deformation decreased.

Finally, from the single-factor part-forming simulation, it can be seen that the greater the curing pressure, the smaller the relative maximum deformation. At the same time, it can be seen from figure 15 that when the pressure reaches the appropriate range, increasing the pressure has a limited contribution to the accuracy of the part. During the simulation process, it was found that if the maximum deformation was reduced by 0.004 mm by increasing the pressure, the corresponding mold deformation increased by approximately 0.001 mm. Therefore, blindly increasing the pressure will result in less profit and affect the life of the mold. It is reasonable to set the pressure to 12 MPa (±0.5 MPa).

4.2. Molding process parameters of optimal result under multi-factor conditions
After analyzing the individual influence and mechanism of each factor, this section comprehensively considers a variety of factors to explore whether there is a coupling effect among the factors that affect the molding accuracy to explore the optimization plan of the molding process. The multi-factors include four process parameters: curing temperature, heating rate, curing pressure, and demolding temperature. The final optimal solution was obtained through a comprehensive analysis and comparison of the four parameters.

If the four parameters take n different values, different process parameter schemes can be obtained. Considering that the process parameter matrix generated by the four parameter variables is relatively complicated, a simplified research method is proposed, which involves first fixing the demolding temperature and heating rate according to the optimal value obtained in the single-factor simulation and changing the value of the curing temperature and curing pressure to obtain the process parameter matrix. After obtaining the optimal solution for the curing temperature and curing pressure, the demolding temperature and heating rate were changed to obtain the optimal solution for these two parameters. Finally, the optimal solution of these four
parameters is obtained, and eventually, the optimization scheme of the molding process can be obtained. The research path is illustrated in figure 16.

4.3. Simulation results and discussion

This experiment included sets of different process parameter simulations, and the values of the four parameters are listed in table 7. The general idea of the simulation can be summarized as: (1) fix the demolding temperature and the heating rate at 30 °C, and 1.486 °C min⁻¹, respectively; (2) change the values of curing temperature and curing pressure, as shown in table 7, to obtain the matrix, and obtain the optimal curing temperature and curing pressure by comparing the results; (3) then fix the curing temperature and curing pressure to the optimal value, change the values of the demolding temperature and heating rate, as shown in table 7, to obtain the matrix, and obtain the optimal demolding temperature and heating rate by comparing the results.

In this section, the maximum deformation is selected as the comparison parameter in Geomagic Control to compare the different groups. The comparison results are shown in figure 17. The maximum deformation in the results was a negative deviation from the part surface. As shown in figure 17(a), the deformation of the part fluctuates with the change in the curing pressure and reaches the minimum value when the pressure is 11.5 MPa. In the single-factor simulation, the deformation decreases with an increase in pressure, which shows that the coupling effect of multiple factors has a certain impact on the deformation of the part, resulting in a change in the minimum point. In addition, the reason for the change may also be an inevitable error in the simulation process. As shown in figure 17(a), the deformation of the part fluctuates slightly with the change in the curing temperature, indicating that the curing temperature has little influence on the control of the deformation of the part.

![Figure 16. Research path of multi factor simulation.](image)

![Figure 17. Multi-factor simulation results: (a) effect of curing temperature and pressure on deformation; (b) effect of demolding temperature and heating rate on deformation.](image)

| Heating rate °C min⁻¹ | Platform pressure /MPa | Demolding temperature °C | Curing temperature °C |
|-----------------------|------------------------|--------------------------|-----------------------|
| 1.27                  | 11                     | 30                       | 115                   |
| 1.375                 | 11.5                   | 40                       | 120                   |
| 1.404                 | 12                     | 50                       | 125                   |
| 1.486                 | 12.5                   | 60                       | 130                   |
| 1.65                  | 13                     | 70                       | 135                   |
| 1.74                  | 13.5                   | 80                       | 140                   |
As shown in figure 17(b), the deformation of the part fluctuates with the change in the heating rate and reaches a minimum value at 1.486 °C min$^{-1}$. In addition, the deformation of the part fluctuates slightly with the change in the demolding temperature; however, in general, it increases with the demolding temperature. The influence of the heating rate and demolding temperature on the deformation of the part is consistent with the influence of the aforementioned single factor.

Synthesizing the single-factor and multi-factor simulation results, the theoretically optimized process parameters were obtained at a heating rate of 1.486 °C min$^{-1}$, curing pressure of 11.5 MPa, curing temperature of 125 °C, and demolding temperature of 30 °C. Figure 18 shows the comparison results of deformation before and after optimization, and the molding accuracy after optimization was significantly improved.

5. Conclusion

The study used the finite element simulation method to predict the curing distortion of a foam-filled composite part with a free-curved surface, and carried out digital measurement and reverse modeling experiments to verify the effectiveness of the simulation model. Finally, the forming process parameters of the part were optimized to obtain the following conclusions:

The finite element simulation analysis model of a foam-filled composite part with a free-curved surface established in this study can effectively predict the curing deformation of the part. The deformation and spring-back results obtained by the simulation coincide with the manufacturing results of the real part. The overall error is less than 1 mm, and the partial error is between 1 mm and 1.5 mm;

Through the simulation analysis of the single factor variables of the forming process parameters, this study determined the basic range of the optimal forming process parameters of the part: the reasonable curing platform temperature range is 120 °C–130 °C; the heating rate range is 1.404 °C/ min$^{-1}$–1.65 °C min$^{-1}$; the demolding temperature range is 25 °C–30 °C; the curing platform pressure range is 11MPa–12MPa;

Through multi-factor coupling simulation analysis, it was found that the coupling effect between multiple factors had a certain impact on the molding result. The optimal molding process parameters for the foam-filled free-curved surface composite part are heating rate of 1.486 °C min$^{-1}$, curing pressure of 11.5 MPa, curing temperature of 125 °C, and demolding temperature of 30 °C. Using the above parameters, the maximum deformation of the test piece was reduced to 2.2988 mm. The curing deformation of the part was significantly lower after process optimization than before.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare no conflict of interest.

Date access statement

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