Finite Element Simulation of the Autoclave Curing Process of Aerospace Resin-based Composite Material

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Abstract. Due to the influence of the wall thickness, uneven heat transfer, and heat generation inside the resin during the molding of the composite material, the uneven temperature field distribution of the composite material is caused. This paper uses ABAQUS to perform finite element simulation on the temperature field of the forming process and obtains the distribution of the internal temperature field of the composite material. On the premise of obtaining the temperature field, through thermo-solid coupling simulation experiment, the influence of various factors on the entire curing process is compared. Based on the use of finite element simulation software, several comparative tests were carried out, and the residual stress problems in the curing process were verified by calling the stress and strain values of representative points. This article focuses on the analysis of temperature and energy data in heat transfer and 15 sets of stress-strain data under coupling action. On the premise of giving the reasons for each data, the accuracy and practicality of the data are analyzed.

1. Introduction

Resin-based composite began to rise in the 1960s. Due to their various excellent properties, such as high strength ratio and specific modulus, anisotropy, material structure integration, etc., their application range is very wide, especially in the Aerospace industry \cite{1, 2}. There are also various molding processes for resin-based composite materials, such as compression molding, autoclave molding, winding molding, and hand lay-up molding \cite{3}. The autoclave forming process is mainly carried out in the autoclave and is one of the important processes for producing high-quality composite structural parts \cite{4}. It can be seen from Figure 1 that in the autoclave molding process, the factors that affect the performance of the final product mainly include: materials, temperature, air pressure, design schemes and thermochemical reactions \cite{5}. The uneven temperature field will cause uneven curing, which will cause deformation and quality problems. The entire molding process includes the coupling effect of multiple fields, and there are coupling problems between chemical fields and temperature fields and other fields in the curing stage \cite{6}. To produce high-performance products, it is necessary not only to develop the theory of multi-field coupling but also to compensate for temperature unevenness by other means \cite{7}. To compensate for temperature unevenness, it is necessary to understand and study the distribution of the internal and external temperature fields of the parts throughout the process. Loos \cite{8} et al. used the modular approach to study the curing process of laminates for the first time and proposed a mathematical model describing heat conduction, resin flow and residual stress. Bogetti and Giliespie \cite{9, 10} studied the 2-D curing simulation of thermosetting
thick-section composites. They considered the coupling of heat conduction and curing kinetics, and predicted the temperature, curing degree distribution and autoclave temperature at any cross-sectional position. The relationship in history, Oh, and Lee [11] used general-purpose finite element software to simulate and solidify thick-section glass/epoxy composite laminates in three dimensions and gave the temperature field inside the component and the pressure field inside the resin. After grasping the internal and external temperature field distribution of the part, it is also necessary to study the stress and strain changes of the part under the combined action of multiple factors through a thermo-solid coupling simulation experiment. This can not only verify the correctness of the temperature field theory but also obtain the Mode of action and impact. Temperature directly affects curing degree, viscosity, and preventive measures for voids, and indirectly affects factors such as resin flow and resin pressure. Therefore, it is very important to study the influence of the temperature field on the molding process of resin matrix composites [12, 13].

Figure 1. Influencing factors in the curing process of composite materials

In this article, a series of comparative experiments based on ABAQUS simulation is used to verify the basic theory of residual temperature field and improve its basic theory. Under the premise of using ABAQUS, the temperature field data and temperature change curve can be obtained through heat transfer simulation, so that the distribution of the internal and external temperature fields of the part can be obtained. Through thermo-solid coupling simulation, the change characteristics and stress-strain curves of composite parts under the coupling action of temperature field and chemical field can be obtained. Thermo-solid coupling simulation can not only verify the correctness of the temperature field distribution but also understand the influence of various factors on the entire curing process. Throughout the simulation process, the combination of experimental data and the data required by the actual process can provide a basis for the actual production process.

2. Finite Element Simulation and Theoretical Model

2.1. Theoretical Model

The finite element theory modeling is the formula derivation and verification of the whole process through basic theoretical knowledge, mainly in the following two aspects: 1. Mechanical theory modeling. 2. Theoretical modeling of heat transfer. Theoretical analysis is carried out through thermo-solid coupling [14-16].

The theoretical equations of physics are as follows:

Density:
\[ \rho = \frac{P_{op} + P}{R M_w T} \]  

(1)

Where, \( P_{op} \): operating pressure, \( P \): local gauge pressure.

Viscosity:

\[ \mu = \mu_0 \left( \frac{T}{T_0} \right)^{3/2} \frac{T_0 + S}{T + S} \]  

(2)

Where, \( \mu \): viscosity (kg/ms), \( \mu_0 \): reference viscosity (kg/ms), \( T \): quiet temperature (K), \( T_0 \): reference temperature (K), \( S \): effective temperature reflecting gas properties (K).

Thermal conductivity:

According to the basic knowledge of fluid mechanics and heat transfer, the energy equation of solid areas such as parts, tooling and auxiliary materials can be expressed as:

\[ \rho C_p \frac{\partial T}{\partial t} = \nabla(\gamma \nabla T) + \dot{q} \]  

(3)

Where, \( \rho \), \( C_p \), \( \gamma \): the density, specific heat and thermal conductivity of solid materials, \( \dot{q} \) is the energy source item. For tooling and auxiliary materials, this item is zero.

2.2. Experimental Program

According to different influencing factors, ABAQUS is used to numerically simulate the temperature field of composite material components [17].

Table 1. Experimental summary table.

| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| Temperature | 0 | 0 | 0 | H | M | L | H | H |
| Pressure   | H | M | L | 0 | 0 | 0 | H | M |
| Number     | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Temperature | H | M | M | M | L | L | L |
| Pressure   | L | H | M | L | H | M | L |

Where, 0: No item, H: High level, M: Medium level, L: Low level.

3. Results and Discussion

3.1. Heat Transfer Model

Select representative data from these data. The strain data does not change much in the thickness direction of the long plate, so only the value change curve in the two horizontal directions is required. Select the maximum amount of stress on the plane in all directions. Figure 2. shows the strain diagram of the center point along the XY direction.
The residual stress is negative in the middle of the long plate and positive in the edge area, which can explain the common edge warping of composite materials after curing. Figure 3. shows the strain cloud diagram described.

3.2. Thermo-solid Coupling Model

In the thermo-solid coupling simulation experiment, a total of 15 sets of comparative test schemes are set up. The best curing temperature and air pressure of this kind of material can be found in the composite material manual, and it is the 11th group in the comparative test plan, medium-temperature and medium pressure. The purpose of setting up other groups is to verify that the load environment is indeed the best.

For groups 1-3, since there is no air pressure load, in the first half, the strain of the workpiece is always in a linear increase state, and the strain of the workpiece is reduced until the cooling stage.

For groups 4-6, Only applying air pressure, the resin in the whole process is liquid, and the carbon fiber material does not change, so it should be a horizontal straight line, which has no reference value, and there is no need to select its data to make a curve here.

The 7, 8, and 9 groups apply a temperature load 20% higher than the best external heat radiation, and apply three different air pressure loads of "high, medium, and low". It can be seen intuitively from the data graph that the three sets of data change in the first and middle stages.

10,11,12 groups apply the best temperature, and apply three kinds of air pressure of "high, medium and low". When under the optimal temperature load, it can be seen intuitively from the figure that the air pressure can determine the curve change of the whole process.

The characteristics of the last three sets of data perfectly verify that the temperature has the best temperature. Table 2. shows the strain values of the simulation results.
4. Conclusion
This design aims to use ABAQUS to perform finite element simulation on the temperature field of the molding process to obtain the distribution of the internal temperature field of the composite material, provide a theoretical basis for perfecting the molding of composite aircraft siding structures, and improve the necessary basis for guiding process optimization later.

1) Analyze the characteristics and difficulties of the resin matrix composite autoclave molding process based on finite element simulation, and analyze the research status given the difficulties.

2) Established a theoretical model of heat transfer based on heat transfer and energy exchange. On the premise of consulting a large number of documents, a theoretical model related to its related parameters was established.

3) By extracting the temperature and energy change data at the center point, the distribution and accurate parameters of the temperature field inside the entire elongated plate are obtained. Can guide related process theory.

4) By extracting the strain data at the center point and the stress data at the five boundary points, the overall strain and stress distribution and more accurate parameters of the entire long plate are obtained. The reasons for various situations under the coupling effect are analyzed, and guidance can be given to improve the process of production efficiency.

5) Analyze the temperature and energy data in heat transfer and 15 sets of stress and strain data

**Figure 4. Strain curve**

**Table 2. Simulation strain value**

| Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| Strain value | 6.23 | 6.21 | 6.17 | 0   | 0   | 0   | 1.43 | 4.51 |
| Number   | 9   | 10  | 11  | 12  | 13  | 14  | 15  |     |
| Strain value | 1.89 | 1.18 | 1.20 | 1.24 | 1.42 | 4.53 | 3.24 |     |
under coupling action. The reasons and shortcomings of each data are given, and the accuracy and practicality of the data are analyzed. This data can provide a basis for process production.

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