Research on Forming Process of Aviation Composite Material Based on Finite Element Simulation

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Abstract. The temperature field by influenced during the curing process of the autoclave, the composite material laminate produces thermal stress and curing residual stress resulting in deformation. Hence, the product is difficult to achieve the expected goal. In this paper, finite element analysis of composite laminates is carried out by using ABAQUS software. For the composite prepreg unidirectional zone, the finite element simulation of the temperature distribution, stress distribution and deformation of composite laminates is carried out during the curing process. The mathematical model of composite curing is established, and the curves of stress and temperature with time are obtained. The influence of various factors on the curing effect is obtained. The influence of factors such as autoclave holding temperature, heating rate, gas pressure in the tank and layup angle on the temperature field and stress field of composite laminates are discussed by finite element method. Through the method of finite element model, time and experiment cost can be saved effectively, which provides a powerful theoretical basis for actual production.

Keywords: Composite material laminate; Finite element simulation; Temperature field analysis; Stress analysis.

1. Introduction

Autoclave molding is currently the most commonly used molding method for composite material molding for the molding method of fiber-reinforced composite materials. It can be cured under the curing cycle, pressure and temperature within the scope of its use requirements, so the autoclave is widely used in the production of advanced aerospace composite materials[1-3]. However, there are many factors in the curing and molding of composite materials that affect the final curing quality. So far, the numerical simulation research of composite material curing has made steady progress[4-7], but there is still no very accurate tool to predict its curing effect in the analysis of composite material curing for autoclave molding. In recent years, many scholars have been working hard to reduce the influence of these factors on the solidification of composite materials. Some scholars also analyze the curing process of autoclaves by studying the convection during the curing process, the temperature field distribution function[8], different composite material parameters[9] and the residual stress during the cooling process[10].

At present, no domestic scholar has conducted a systematic analysis on the influencing factors of composite autoclave molding process. Therefore, in this work, thermosetting resin-based composites will be study, use ABAQUS to establish a finite element model of composite laminates, simulate the curing and molding process of composite laminates, obtain the temperature field and stress of composite laminates size. This work simulates and analyzes the forming process of composite laminates and studies.
the effects of different factors on the curing stress of composite laminates formed by autoclave, and optimizes the forming process curve. This work will also provide practical reference and guidance for producers.

2. Curing Simulation of Composite Laminates

2.1. Geometry Model and Mesh Division
The ABAQUS finite element analysis software was used to establish the solid three-dimensional finite element calculation model of the prepreg unidirectional tape composite laminate and the aluminum table for curing. The dimensions of the composite laminate and the aluminum table are 100*100*20mm and 150*150*50mm, respectively. Along the thickness direction, every 5 layers of composite materials are divided into one layer of elements, and three-dimensional solid elements are used for meshing. The unit family is heat transfer, the unit type is DC3D8, the unit size is 5, and the number of units is 8000.

2.2. Material Model and Stress-strain Model
The AS4/3501-6 material model is used to simulate the carbon fiber prepreg unidirectional tape, set the 1-axis direction as the fiber direction, set the AS4/3501-6 composite layer thickness to 0.2, initially set the layering angle to 0°, the number of layers is 100 layers. During the curing process of composite laminates, residual stresses are generated and consist of two parts. One part is the thermal stress determined by the temperature, and the other part is the stress caused by the volume shrinkage related to the curing reaction. The residual stress caused by these processes will cause the deformation of the composite structure.

The composite material selected in this research is a thermosetting resin matrix composite material (prepreg unidirectional tape) AS4 and the matrix is 3501-6.

2.3. Boundary Conditions of Laminates
In the initial analysis step, the interaction of heat transfer is created, the boundary condition of the bottom surface of the aluminum table is completely fixed and then a predefined temperature field of 300k is created, which is an ambient temperature of 27°C. Create the heat transfer analysis step step-1, apply temperature boundary conditions to the outer surface of the aluminum table and the outer surface of the laminate. The temperature change amplitude is in the form of a table. The specific values are shown in Table 1. Secondly, when the temperature field distribution of the composite laminate is obtained, the stress distribution caused by the temperature is analyzed. On the basis of model 1, the heat transfer property of step-1 in model 1 is replaced by temperature-displacement coupling. After changing the grid type, the element family is changed to temperature-displacement coupling, the element type is changed to DC3D8, the element size is unchanged, and the number of elements is unchanged, and model 2 is obtained. Finally, in the case of obtaining the thermal stress distribution of the composite laminate. Add a pressure load in the step-1 analysis step of model 2, apply pressure to the top and surrounding of the laminate, simulate the pressurization process in the autoclave, obtain model 3. After experiencing the initial pressure increase at one atmospheric pressure, then maintain the pressure and finally unload the pressure, the amplitude of the pressure is shown in Table 2.

Table 1. Amplitude of temperature change.

| Time/s | 0   | 1800 | 5400 | 6600 | 14100 | 17100 |
|--------|-----|------|------|------|-------|-------|
| Temp/k | 300 | 390  | 390.1| 450  | 450.1 | 300   |

Table 2. Amplitude of pressure change.

| Time/s | 0       | 300    | 16800 | 17100 |
|--------|---------|--------|-------|-------|
| Pressure/MPa | 0.1 | 0.2  | 0.2001 | 0.1 |

2.4. Numerical Simulation Results
According to the above three models, the simulation results of the three models of composite laminates

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can be obtained respectively as shown in Figure 1, 2, and 3. Respectively, are the temperature field distribution and stress-strain cloud diagrams of the laminate under different conditions, paving the way for the following discussion of the influence of different factors on the composite laminate.

![Cloud diagram of temperature field distribution of laminated board cross-section.](image1)

**Figure 1.** Cloud diagram of temperature field distribution of laminated board cross-section.

![a) The thermal stress distribution cloud diagram of the laminated plate b) The principal strain cloud diagram of the laminated plate.](image2)

**Figure 2.** a) The thermal stress distribution cloud diagram of the laminated plate b) The principal strain cloud diagram of the laminated plate.

![a) Cloud diagram of stress field distribution of laminated plate b) Cloud diagram of principal strain of laminated plate.](image3)

**Figure 3.** a) Cloud diagram of stress field distribution of laminated plate b) Cloud diagram of principal strain of laminated plate.

3. **Influencing Factors of Curing Process**

During the autoclave curing of composite laminates, there are usually many factors that affect the final cured state of the laminate. Therefore, this section will further discuss the effects of various factors on the curing stress of composite laminates by changing the holding temperature, heating rate and layup angle during curing.

3.1. **The Influence of Holding Temperature on Stress in the First Stage**

Analyze the influence of the temperature holding on the curing stress of composite laminates. Change the temperature amplitude based on the temperature boundary condition in the analysis step step-1 in Model 3, select 360k, 390k, 420k for the heat preservation temperature. The stress distribution cloud diagram in the analysis result is shown in Figure 4. Take the center point of the composite laminate in the analysis result to get the time-stress curve shown in Figure 5. It can be seen from Figure 5 that the holding temperature has an effect on the curing stress of the composite laminate. The high holding temperature will slightly increase the thermal stress of the composite laminate during the heating.

![Principal stress distribution cloud diagram a) 360k b) 390k c) 420k.](image4)

**Figure 4.** Principal stress distribution cloud diagram a) 360k b) 390k c) 420k.
3.2. The Effect of Heating Rate on Stress

The heating rate of the temperature process curve is an important factor affecting the curing stress of the composite laminate. By changing the heating rate in the analysis step, changing the temperature boundary conditions based on the analysis step step-1 in Model 3, and changing the time in the amplitude table, different heating rates can be obtained. The layering method of the composite laminate is $0_{20}$, and the heating rate is 1.5k/min, 3k/min, 4.5k/min. The stress distribution cloud diagram in the analysis result is shown in Figure 6 a) b) c). Take the center point of the composite laminate in each analysis result to obtain a time-stress curve, as shown in Figure 7. It can be obtained from Figure 9 that the heating rate has an effect on the curing stress of the composite laminate, and the heating rate is positively correlated with the stress. A lower heating rate can significantly reduce the stress of the laminate and make the temperature field of the laminate more uniform.

![Stress distribution cloud diagram under different heating rates](image)

**Figure 6.** Stress distribution cloud diagram under different heating rates a) 1.5k/min b) 3k/min c) 4.5k/min.

![Center point time-stress curve at different heating rates](image)

**Figure 7.** Center point time-stress curve at different heating rates.

3.3. The Influence of Ply Angle on Stress

According to the actual product use, composite laminates have various layup methods. This section only gives four simple examples to verify the impact of lay angle on the stress of composite laminates. In this section, the composite laminate model is re-established, and the layup methods of $[0_14]$, $[0_{7}/90_{7}]$, $[±45_7]$ and $[0_3/±45_3/±45/0_3]$ are used for simulation and discussion. The model uses solid modeling, and the material performance parameters are the same as in Chapter 2. The stress distribution cloud diagram and deformation under different layering conditions are shown in Figure 8 a) b) c) d). It can be seen from the above figure that the difference of the layup method has an impact on the degree of deformation, but also on the form of deformation. When symmetrical layup, the internal stresses of the laminate will balance each other, which has achieved the purpose of reducing deformation.
4. Conclusion

In this paper, by analyzing the influencing factors of composite laminates, a series of finite element models are established using ABAQUS software to discuss the effects of various influencing factors on the temperature field, stress and deformation of composite laminates during curing. Conclusion as below:

1. The effects of the holding temperature on the curing stress of the composite laminate are discussed. Finally, it is concluded that higher temperatures can speed up the curing speed of the composite laminate, but it is easy to increase the inconsistency of the internal temperature of the laminate, while a lower temperature can ensure the quality of the composite laminate. The internal temperature is relatively consistent, but the curing time will be extended accordingly, resulting in a decrease in curing efficiency and an increase in production costs.

2. Explore the effect of curing temperature rise rate on the curing of composite laminates. As the heating rate increases, a large amount of heat accumulates, and the uniformity of the internal temperature field of the laminate decreases, so that part of the heat preservation time is used to balance the internal and external temperature of the laminate and reduce the curing efficiency. While the temperature rise rate is reduced, although the uniformity of the temperature field of the laminate can be controlled, but the use time of the autoclave is prolonged, which will increase the production cost.

3. Explore the effect of the ply angle on the curing of composite laminates. The different layup methods have an impact on the degree of deformation, as well as the form of deformation. When symmetrically laid, the internal stresses of the laminate will balance each other, which has achieved the purpose of reducing deformation.

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