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Research on Molding Temperature Process Parameters of Composite Parts

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Abstract

Composite materials are widely used in the aerospace field due to their excellent properties. However, the curing deformation of the composite part will occur in the forming process, which will cause adverse effects on the forming part, such as the decline of precision and so on. This paper introduces the thermochemical model of composite parts and the influence mechanism of heating rate, curing temperature and demolding temperature in temperature curve on curing deformation, and simulates the curing process of a complex curved part based on ABAQUS finite element simulation software. The correctness of the simulation model is verified by comparing the digital measurement results. Based on the optimized temperature and demolding rate, the appropriate temperature was obtained.

Keywords

Composite materials; Curing deformation; Finite element analysis; Molding; Thermosetting resin; Simulation.

1. INTRODUCTION

Because of the high specific strength, high specific modulus and strong designability, composite materials are widely used, especially in aviation. However, the curing deformation in the process of forming composite parts has a great effect on the accuracy of the part.

The temperature curve in the forming process of composite parts has a great influence on the curing deformation of composite parts. Many researchers are committed to studying the forming temperature curve of composite parts. Olivier and El Sawi [1] found that lower curing temperature can make the deformation of the part smaller, but the curing time is longer. White and Hahn [2-3] found that with the increase of curing temperature, the time to complete the curing reaction decreases, but it will cause incomplete curing. Bogetti and Gillespie Jr [4] research shows that the heating rate will affect the curing sequence along the thickness direction of the part. Theoretically, there should be a specific heating rate to make the part cure inside and outside at the same time. Filleter and Espinosa [5] and Martin [6] proposed new curing processes, such as radiation curing and microwave curing, to reduce the influence of uneven heating on curing deformation.

The above conclusions are mainly from the theoretical analysis, and this paper will use the simulation model of the complex composite parts to explore. In this paper, the thermochemical model of the composite part is used to simulate and optimize the forming process of a composite part by ABAQUS software. The influence mechanism of curing temperature, heating rate and demolding temperature is verified, and the maximum deformation of the part is reduced by optimization.

2. MECHANISM OF TEMPERATURE CURVE AFFECTING THE MOLDING OF COMPOSITE PART

2.1. Thermochemical Model

It is very important to analyze the internal heat transfer of the part in the molding process. It is also one of the necessary factors for the simulation and optimization of curing deformation.

In the molding process, there is heat transfer between the composite part and the mold, and a temperature field will be formed inside the composite part. The anisotropy of the composite material leads to the uneven deformation of the composite part, resulting in residual stress. At present, most researchers obtain the temperature field formed by heat conduction in composite materials through Fourier's law of heat conduction [7-9]:

$$\rho_{\mathrm{p}} c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_{xx}\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_{yy}\frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_{zz}\frac{\partial T}{\partial z}) \tag{1}$$

Where ρ_p represents the density of the composite; C_p represents the specific heat capacity of the composite; k_{xx}, k_{yy}, k_{zz} represents the heat transfer coefficient of the composite in different directions; t represents the curing time; T represents the current transient temperature.

However, in the molding process of the composite part, the internal temperature of the composite part will continue to increase, and the resin matrix of composite materials will be cured, contracted, and exothermic, which will affect the temperature field formed by the heat transfer effect of external heat. Therefore, the curing shrinkage and exothermic heat of resin matrix in the forming process of the composite part should be taken into account in Fourier heat conduction law.

The curing reaction of the resin matrix is exothermic:

$$\lambda_{\mathrm{x}} \frac{\partial^2 T}{\partial \mathrm{x}^2} + \lambda_{\mathrm{y}} \frac{\partial^2 T}{\partial \mathrm{y}^2} + \lambda_{\mathrm{z}} \frac{\partial^2 T}{\partial \mathrm{z}^2} + Q = \rho_{\mathrm{c}} C_C \frac{\partial T}{\partial \mathrm{t}} \tag{2}$$

$$\rho_{\mathrm{p}} c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_{xx}\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_{yy}\frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_{zz}\frac{\partial T}{\partial z}) + \dot{q} \tag{3}$$

Where $\dot{q}$ refers to the generation rate of resin-based curing reaction heat of composite materials, all heat generated by resin-based curing reaction per unit time. It is related to the total heat release of resin-based curing shrinkage reaction and the reaction rate of the curing shrinkage process.

$$\dot{q} = \rho_{\mathrm{m}}(1 - V_f) H_\gamma \frac{d\alpha}{dt} \tag{4}$$

Where ρ_m represents the density of resin matrix, V_f represents the percentage of fiber volume in the total volume of composite material, H_γ represents the heat released by curing reaction of resin matrix per unit mass, α represents the degree of curing, and $\frac{d\alpha}{dt}$ represents the rate of curing reaction.

For example, the curing reaction rate of epoxy resin can be expressed as:

$$\frac{\mathrm{d}\alpha}{\mathrm{dt}}=\begin{cases}(K_1+K_2\alpha)(1-\alpha)(0.47-\alpha),\alpha\leq 0.3\\ K_3(1-\alpha),\alpha\leq 0.3\end{cases}$$

$$K_{\mathrm{i}}=A_{\mathrm{i}}\exp(\frac{-\Delta E_{\mathrm{i}}}{RT}),\mathrm{i}=1,2,3 \tag{5}$$

Where K_i is the reaction rate constant of the autocatalytic model; A_i is the frequency factor of the autocatalytic model; ΔE_i is the activation energy of the autocatalytic model; R is the ideal gas constant.

2.2. Influence of Process Parameters Related to Temperature Curve on Forming of Composite Parts

The temperature field has a great influence on the forming accuracy of the composite part. The composite part is affected by double heat sources in the forming process, including the external temperature field and the curing heat release of the resin inside the part. It can be seen from formula (1-3). Both of them work together to form an uneven temperature field, and then cause uneven deformation of the part. Among the external temperature conditions, the curing temperature, heating rate, and demolding temperature have a great influence on the curing deformation.

Increasing the curing temperature can accelerate the curing speed and shorten the curing time. It can be seen from formula (5). If the curing temperature is too high, the value of K will increase, and then the curing rate will be increasing. While the temperature is too high, the fluidity of prepreg will decrease rapidly due to the fast curing speed. Especially for large thin-walled and complex composite products, the outer layer of the products cures much faster than the inner layer when the temperature is too high. When the curing temperature is too low, the rise of curing temperature will slow down, the curing efficiency will decline, and the phenomenon of low curing degree will appear, which will also affect the forming precision.

Similarly, the heating rate has a direct effect on the temperature field of the part. The appropriate heating rate can make the part have enough time for heat exchange and heat conduction. Similar to the curing temperature, the heating rate will also affect the curing efficiency. It can be seen from formula (3-4). The increase in the heating rate will lead to an increase in the curing rate, which will affect the molding accuracy of composite materials.

Demolding temperature is a process parameter that is easy to be ignored. The demolding temperature will affect the plasticity of the part in the demolding process and the deformation and internal stress of the part after demolding.

Therefore, the appropriate curing temperature, heating rate, and demolding temperature are helpful to the temperature distribution of part forming, and thus reduce the curing deformation in the forming process.

3. FINITE ELEMENT MODEL

3.1. Establishment of Finite Element Model

This paper studies a composite part, as shown in Figure 1, which mainly includes four parts: forming upper and lower metal mold, composite part, and honeycomb sandwich. The upper and lower mold and assembly drawing after drawing are shown in Figure 2.

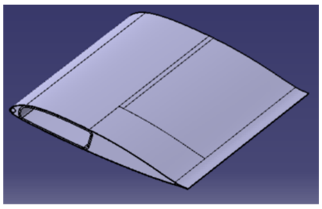
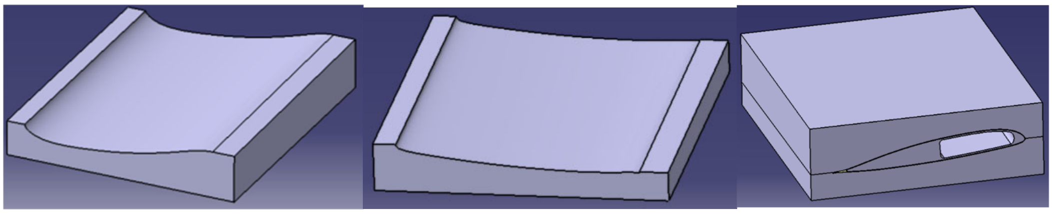


Figure 1. The composite part



(a)Upper mold (b) lower mold (c)Assembly drawing

Figure 2. The part and mold drawing

The material of part is carbon fiber reinforced plastics (3238A/CF3052), and foams are mainly made of A52 foam. The elastic modulus, Poisson's ratio, thermal expansion coefficient, thermal conductivity, and specific heat capacity are mainly set up in the simulation. The material of the outer mold is invar steel, and the material parameters of the mold, such as elastic modulus, Poisson's ratio, density, specific heat capacity, thermal expansion coefficient, and thermal conductivity coefficient, are defined in the simulation.

Table 1. Properties of cellular foam materials

Parameters	Value
Density $\rho m/t/mm^3$	5.2×10^{-11}
Thermal conductivity /mW/(mm·K)	0.031
Specific heat C_m/mJ/(t·K)	4.2×10^{9}
Expansion α_m/°C^{-1}	3.7×10^{-5}

Table 2. 3238A/CF3052 material properties

Parameters	Value
Density ρ_c/kg/mm3	1.76×10^{-9}
Thermal conductivity /mW/(mm·K))	5.43/0.41
Thermal expansion coefficient/°C^{-1}	$0.5\times10^{-6}/35.3\times10^{-6}$
Specific heat C_m/mJ/(t·K)	8.62×10^{8}
Elasticity (Engineering constant)/MPa	E_1=12600, E_2=8300, N_{u12}=0.35 G_{12}=4100, G_{13}=4100, G_{23}=2800

Table 3. Invar steel material properties

Parameters	Value
Density ρm/t/mm3	8.1×10^{-9}
Thermal conductivity /mW/(mm·K)	11
Specific heat C_m/mJ/(t·K)	5.15×10^{8}
Elasticity (Young's modulus / kPa-Poisson's ratio)	125000 0.22

The process conditions of FEA simulation are hot pressing, and the simulation optimization is carried out by ABAQUS software. Referring to the thermochemical model, the temperature applied by the outside is transmitted to the composite part by the mold through heat conduction. Meanwhile, the resin will release heat during the curing process to form an internal heat source, it can be seen from formula (3). The mold will not consider heat loss, and keep the mold temperature change consistent with the curve of the design temperature change. The simulation mainly includes two processes: the curing period and the spring-back of the composite part period, the part is cured first, then the outer mold is removed to complete the spring-back.

During the forming process, the initial pressure of part is added to 6 ± 5MPa after the mold is closed, and then the temperature rises to 70 ± 5 ℃ at a rate less than 1.5 ℃ /min, and the external pressure is added after holding for 30 ± 5min: increase the pressure to (12 ± 0.5MPa), continue to rise to 125 ± 5 ℃, keep the temperature for 135 ± 15min, and then cool to 25 ° C and then depressurize. The spring-back occurs at room temperature. The temperature and pressure loading curve is shown in Figure 3.

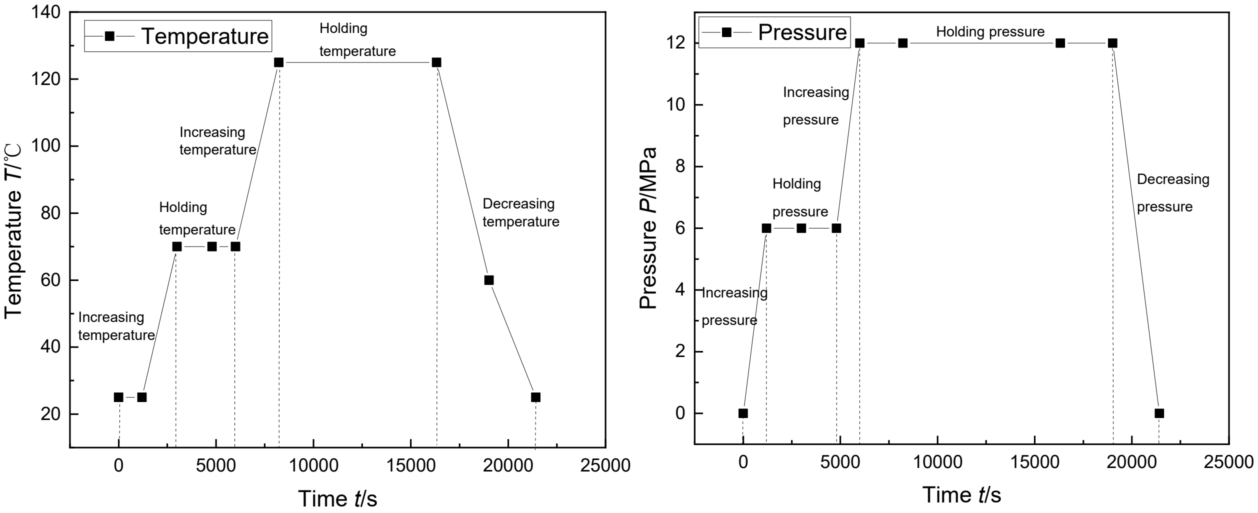


Figure 3. Temperature and pressure loading curve

In the setting of curing parameters, the pressure is applied to the upper surface of the outer mold, and the mold and part are compacted. The lower surface of the outer mold is completely fixed; the relationship between the outer mold and the part surface is set as a surface contact, and the relationship between the honeycomb foam and the part surface is set to be bonded. The deformation of the spring-back still maintains the surface relationship between honeycomb foam and part. Different from the simulation spring-back model in the literature, the honeycomb foam is filled inside the part after molding. The effect of honeycomb foam on spring-back is also considered in the process of spring-back.

The secondary development function of ABAQUS software is applied. The user subroutines of USDFLD, UEXPAN, DISP, and HETVAL are used in the heat conduction curing analysis module, and the user subroutine of UEXPAN is used in the stress displacement module. USDFLD is used to define the initial curing degree. It is used to define the field variable as a function related to time or any other variable in the output variable list. The defined variable can be called by other subroutines to realize data transfer between subroutines. HETVAL is mainly used to define the internal heat generation in heat transfer analysis, which is used to represent the heat flow caused by heat generation in the curing reaction of part HETVAL mainly transfers the temperature change obtained in each increment step to the subroutine of curing degree calculation to obtain the curing degree corresponding to the temperature and realize the coupling of temperature field and curing degree field; DISP is used to impose the temperature boundary condition; UEXPAN is used to express the thermal expansion coefficient of the composite and the chemical reaction shrinkage strain of the resin.

3.2. Analysis and Verification of Simulation Model

The curing process of composite parts mainly includes heating, heat preservation, cooling, and demolding. In the heating stage, the curing reaction of the resin begins to take place, and the material is mainly viscoelastic; in the heat preservation and cooling stage, the resin gradually changes to a glass state, and its modulus also changes from small to large. After the part is cured and cooled to room temperature, the spring-back simulation is carried out. The result of deformation displacement after spring-back is shown in Figure 4.

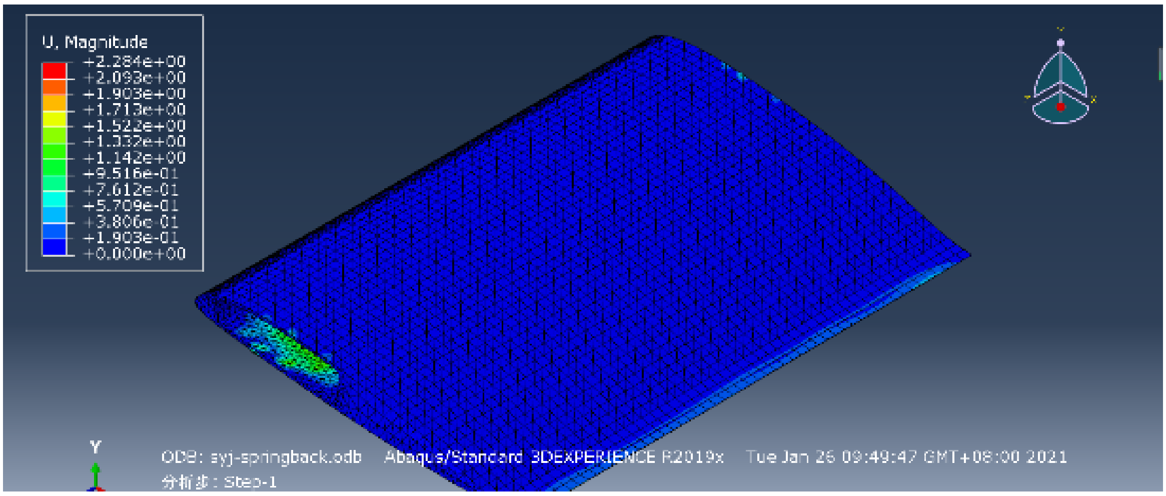


Figure 4. Nephogram of spring-back deformation of the part

It can be seen from the results of spring-back deformation displacement that the maximum offset is 2.284mm, which has a certain optimization space.

After the nephogram of the spring-back simulation is obtained, it is imported into Hypermesh and compared with the design digital model, as shown in Figure 5. The green part indicates that the error is less than 1 mm; the yellow part indicates that the error is between 1 mm and 1.5 mm, and it is the positive error of the designed digital-analog protruding scanning surface. From the error distribution, it can be seen that most of the real surface forming accuracy is high (the error is less than 1 mm). Most of the curvature has an error of 1mm to 1.5mm at the trailing edge, which indicates that there is a certain spring-back at the forming experimental section; there is a certain degree of spring-back at the edge, which is due to the poor load-bearing capacity at the edge, which is easy to deform in the process of stress release; there is a blue dot deformation on the upper surface, which may be due to the deformation caused by the error of mesh fitting surface.

The comparison results between the measurement digital model and the design digital model are shown in Figure 6. Comparing the two results, it can be found that the error trend is similar, and the position of the yellow part is roughly the same, which confirms the theoretical correctness of the simulation model, and can be used in future simulation optimization work.

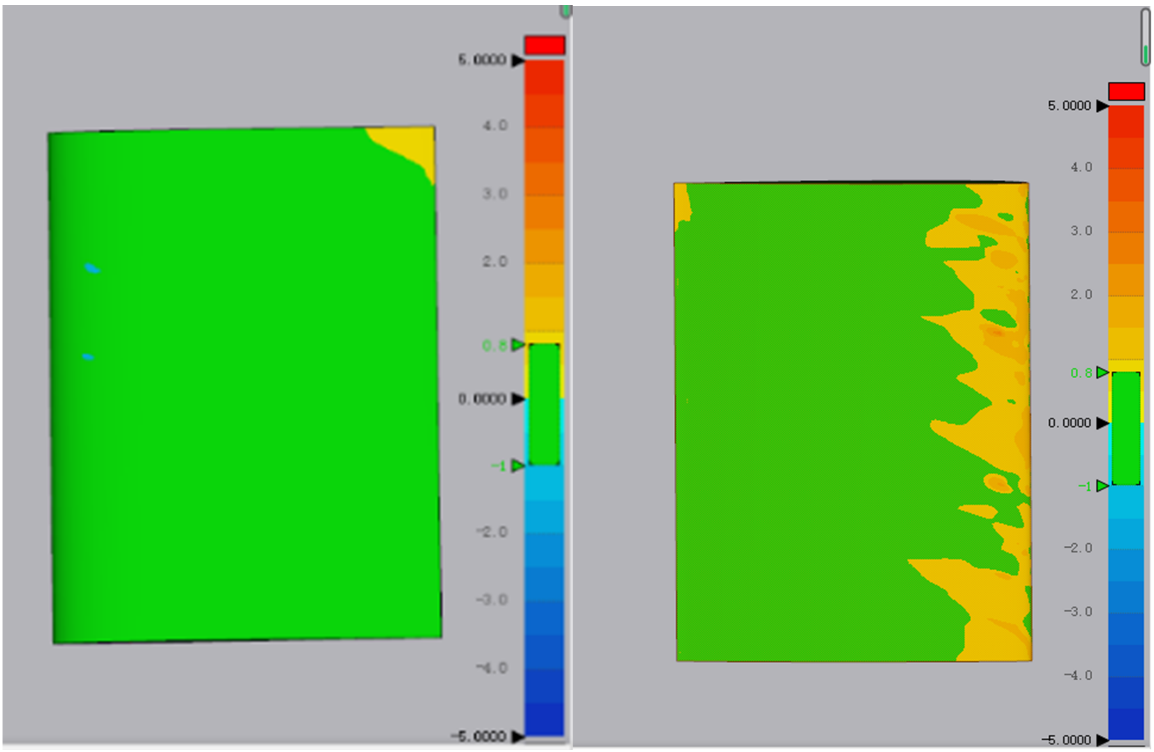


Figure 5. The simulation results are compared with the designed model (the left figure shows the upper surface and the right figure shows the lower surface)

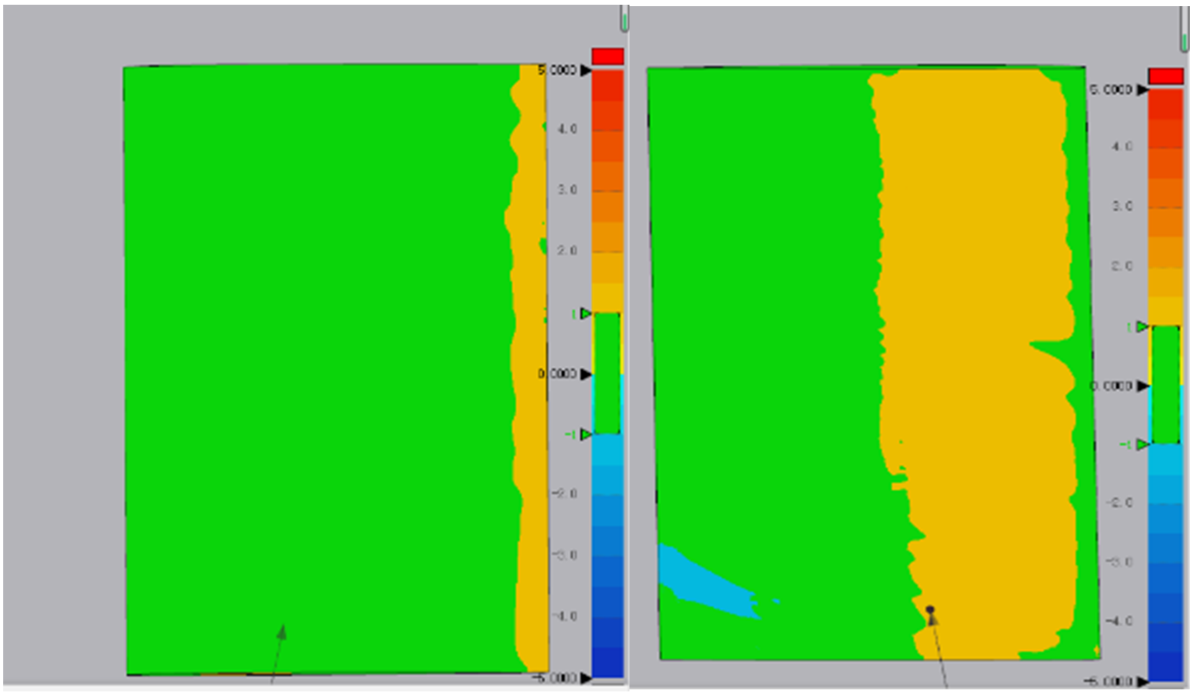


Figure 6. Comparison between the measured results and the designed model (the left figure shows the upper surface and the right figure shows the lower surface)

4. OPTIMIZATION OF PROCESS PARAMETERS

4.1. Optimization results of curing temperature

In the original process, the curing platform temperature is set to 125 °C, in this paper, 125 °C is taken as the middle value, and three groups of data with the curing platform temperature of

110 °C, 120 °C, and 130 °C are selected for simulation analysis. The temperature curve of the four simulation models is shown in Figure 7. Because the trend of simulation cloud map of ABAQUS is consistent and the difference is small, it is difficult to find the changing trend directly from the cloud chart, so only the deformation cloud chart with curing temperature of 120 °C is listed, as shown in Figure 8. The same is true for heating rate and demolding temperature. This is not described in the following article. The maximum deformation of simulation results is compared with the results of Figure 9.

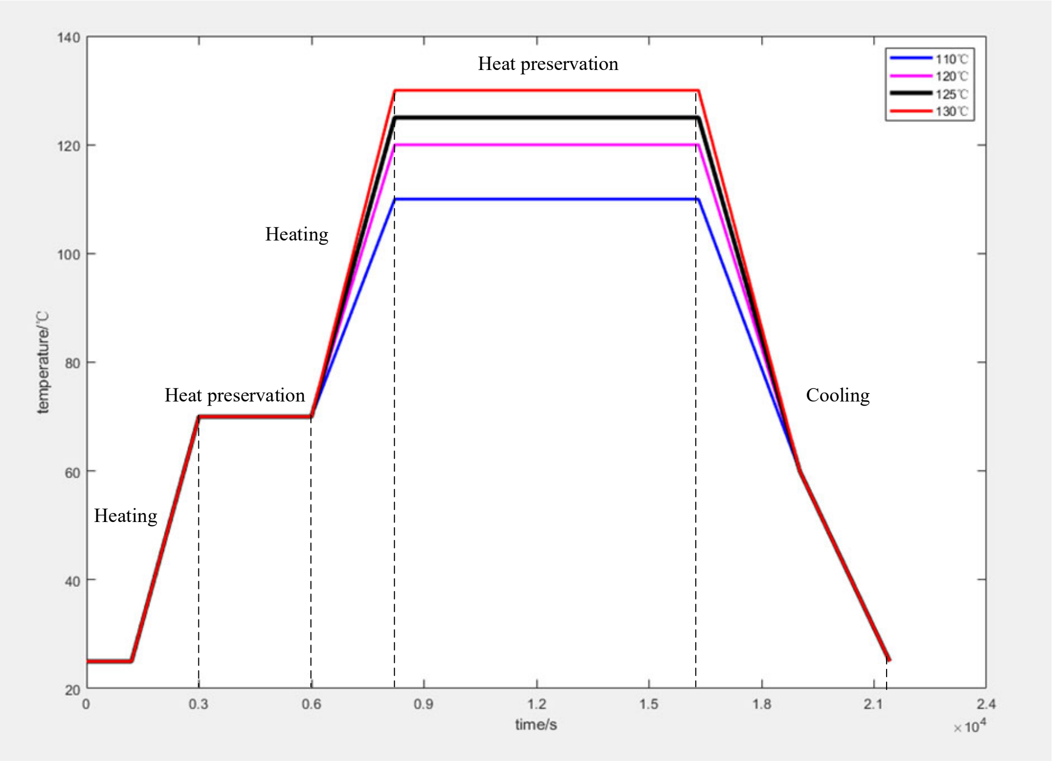


Figure 7. Temperature curve of simulation model under different curing temperatures

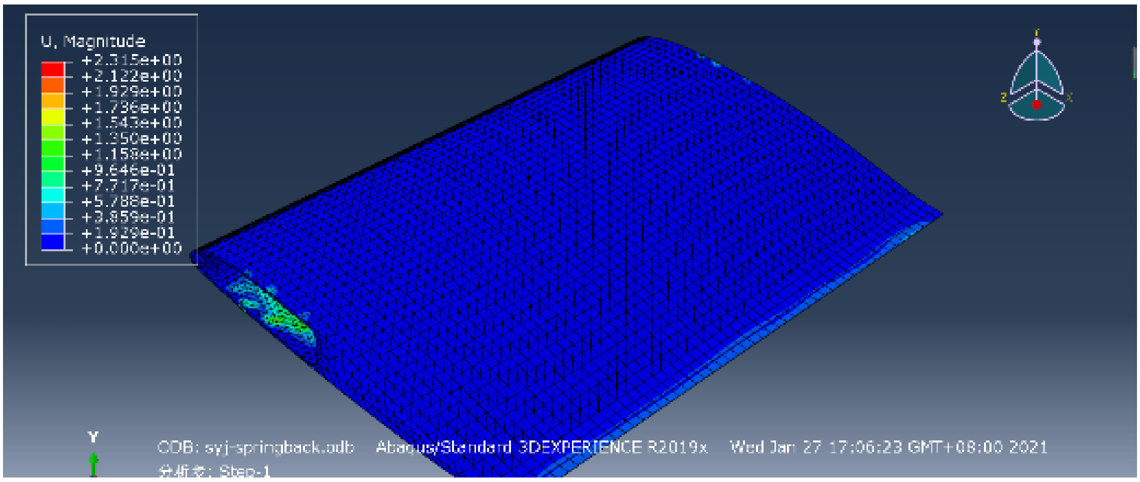


Figure 8. Deformation nephogram of composite part cured at 120 °C

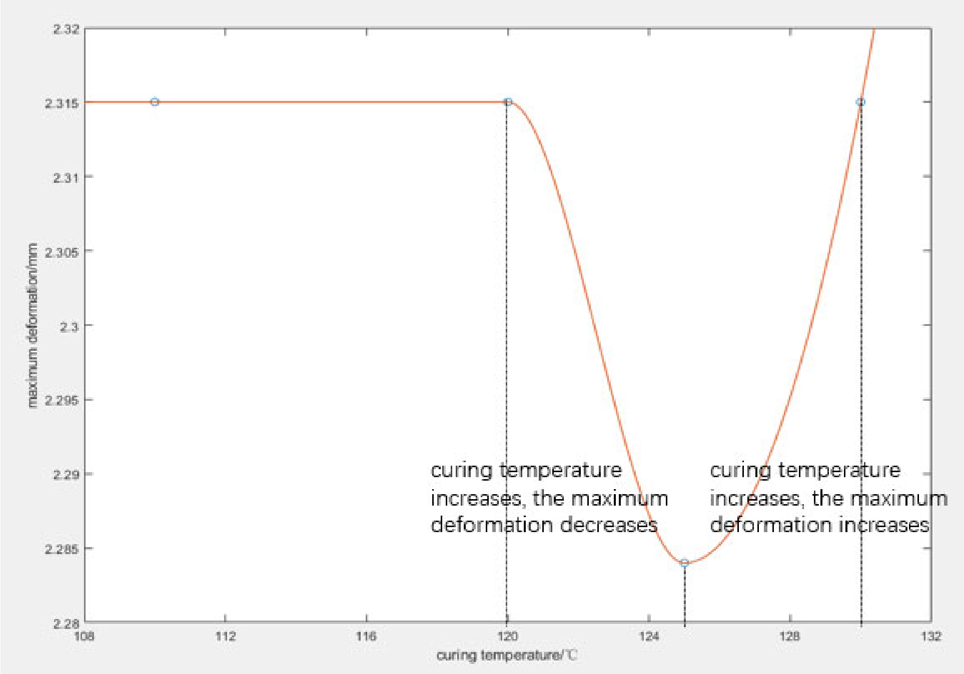


Figure 9. Comparison of simulation maximum deformation under different curing platform temperatures

When the temperature is set at 130 °C, if the temperature is too high, the outer layer temperature is higher than the inner layer temperature, as shown in Figure 10. According to the thermochemical model, the outer layer of the composite part cures faster than the inner layer, resulting in the increase of deformation; when the temperature is less than 125 °C, the curing temperature is too low, the curing efficiency decreases, resulting in the low curing degree, which affects the accuracy of the part. Appropriate curing temperature can improve the curing efficiency, ensure the mechanical properties of the part, and reduce the curing deformation.

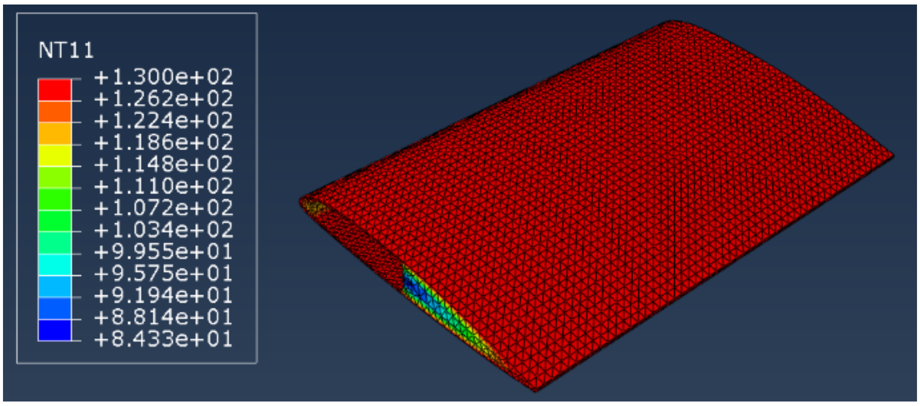


Figure 10. Temperature nephogram at a certain time in the heating stage

4.2. Optimization Results of Heating Rate

The heating rate in the original model is 1.486 °C / min. in this paper, several groups of simulations are made. Only changing the heating rate, several groups of experimental models are selected, including 1.375 °C / min, 1.404 °C / min, and 1.65 °C / min. The temperature curve of the simulation model under different heating rates is shown in Figure 11. When the heating rate is 1.65 °C / min, the temperature curve of the simulation model is as follows, the cloud image of deformation simulation is shown in Figure 12, and the contrast image of spring-back is shown in Figure 13.

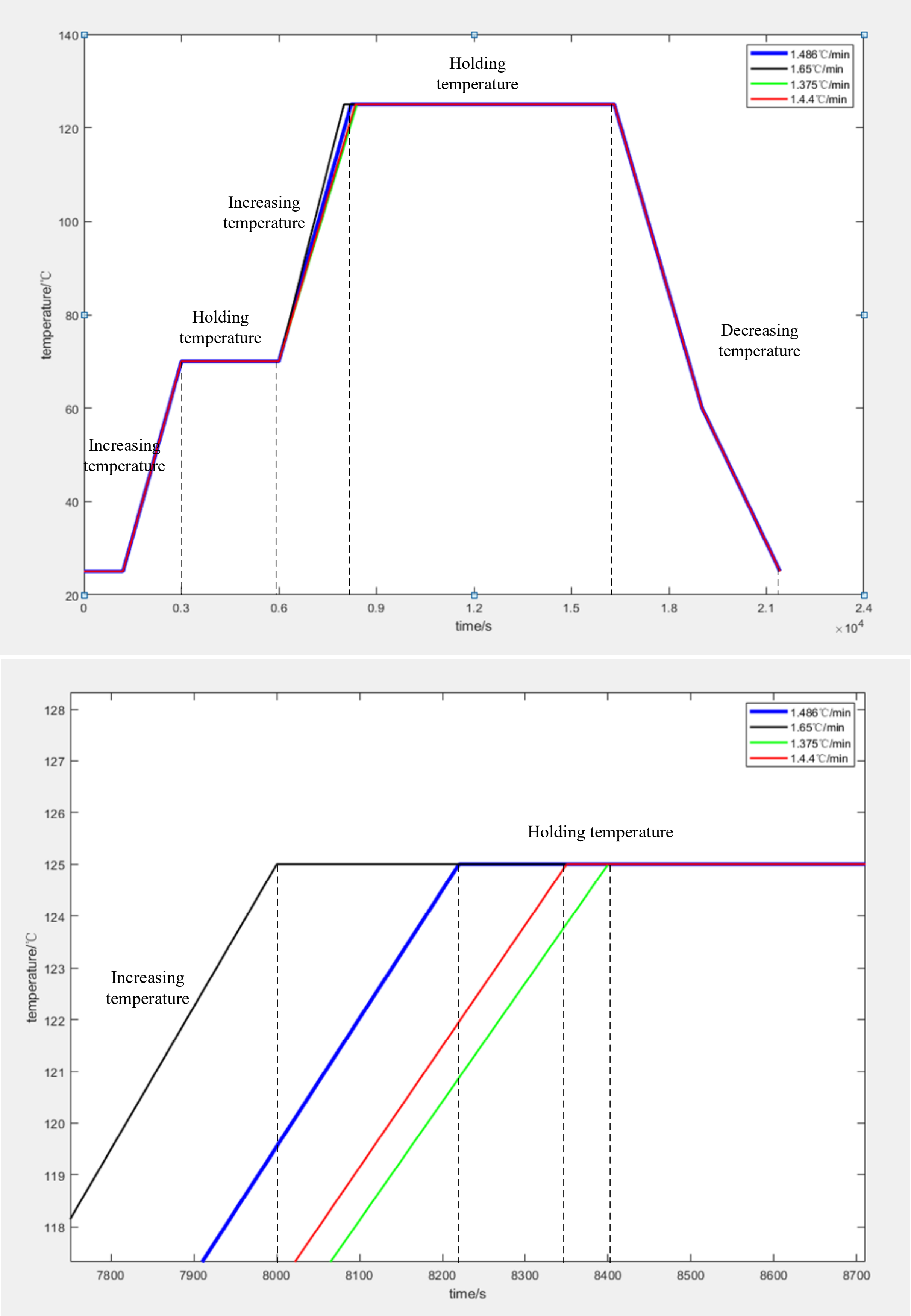


Figure 11. The temperature curve of the simulation model under different heating rates, the right figure is the partially enlarged figure

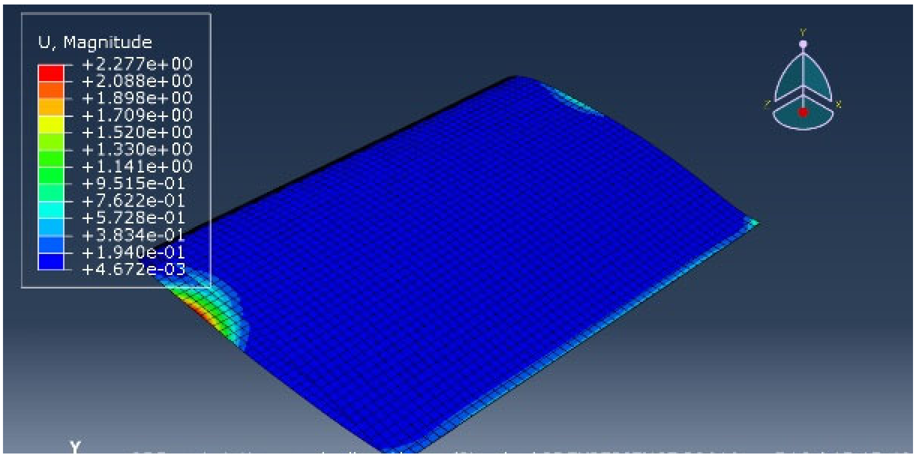


Figure 12. Deformation nephogram of composite part with the heating rate of 1.65 ℃ / min

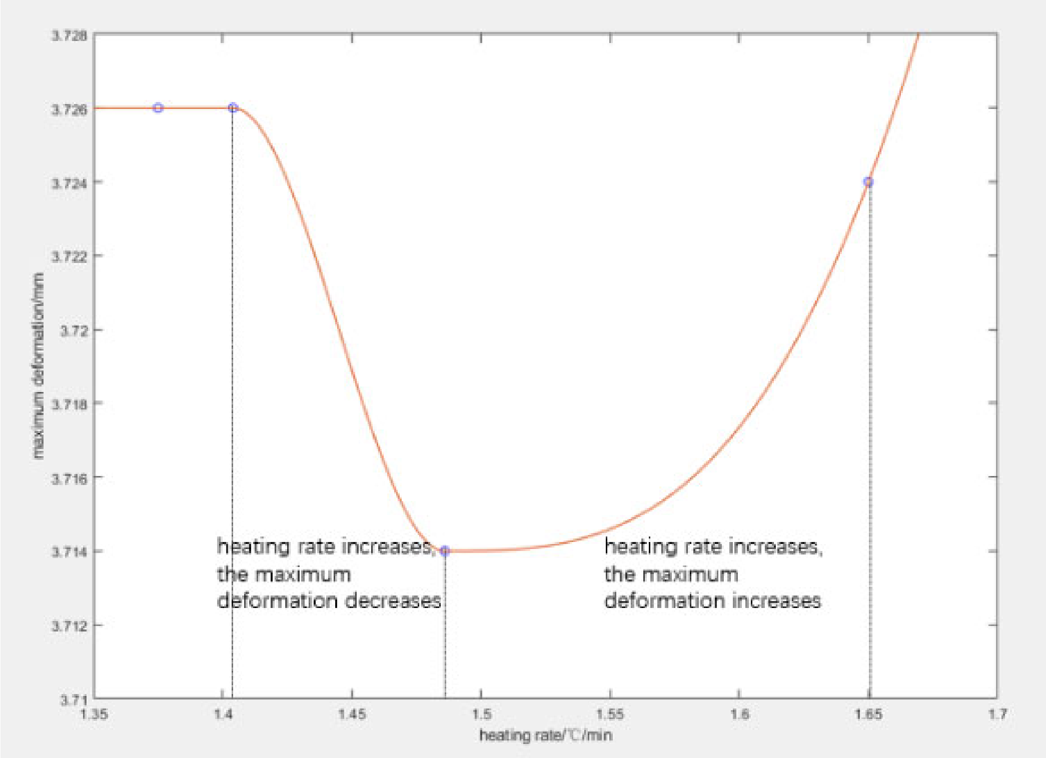
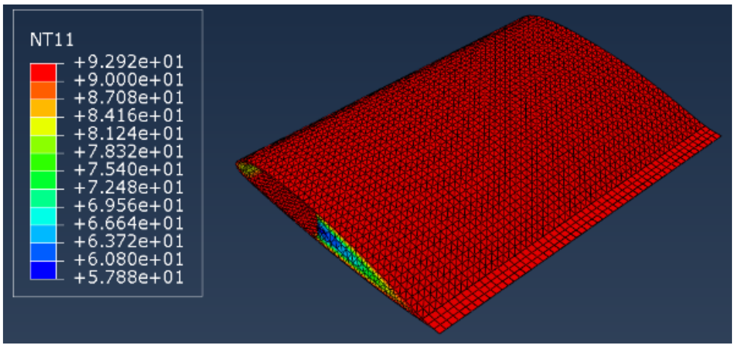
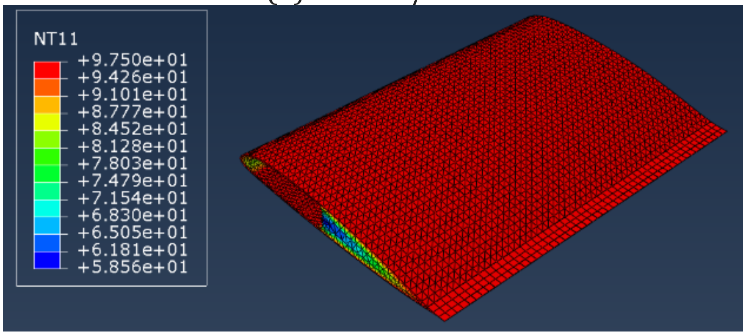


Figure 13. Comparison of maximum deformation under different heating rates

Through simulation and comparison, when the heating rate is less than 1.47 ℃ /min, the curing efficiency becomes slower. Under the condition of constant curing time, the precision of curing molding is not completely reduced; when the heating rate is greater than 1.52 ℃ /min, the temperature distribution will be more uneven, as shown in Figure 14, which leads to the increase of deformation, thus increasing the maximum deformation on the whole. Therefore, the heating rate of curing should be selected reasonably according to the actual situation and various factors to ensure the rapid and efficient curing of the parts and improve the forming quality.



(a)1.375℃/min



(b)1.65℃/min

Figure 14. Temperature distribution at the same time under different heating rates

4.3. Optimization results of demolding temperature

In this paper, the control variable method is used to set the demolding temperature as 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C. The temperature curve of the simulation model under different demolding temperatures is shown in Figure 15. The simulation cloud diagram when the demolding temperature is 50 °C is shown in Figure 16, and the comparison of the maximum deformation is shown in Figure 17.

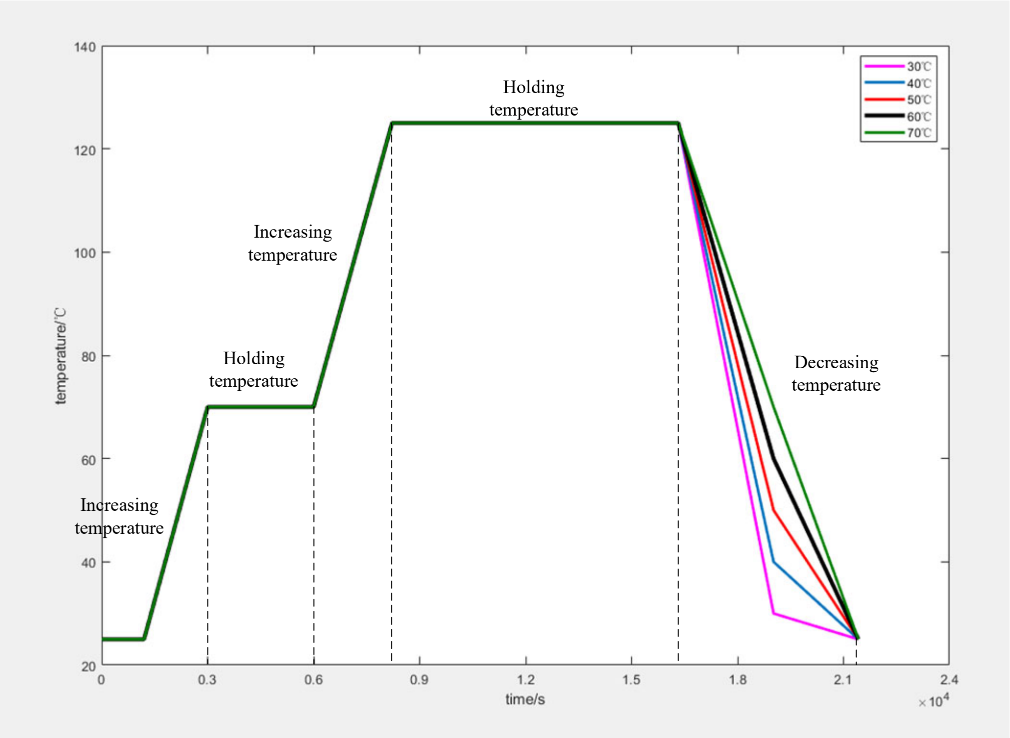


Figure 15. Temperature curve of simulation model under different demolding temperatures

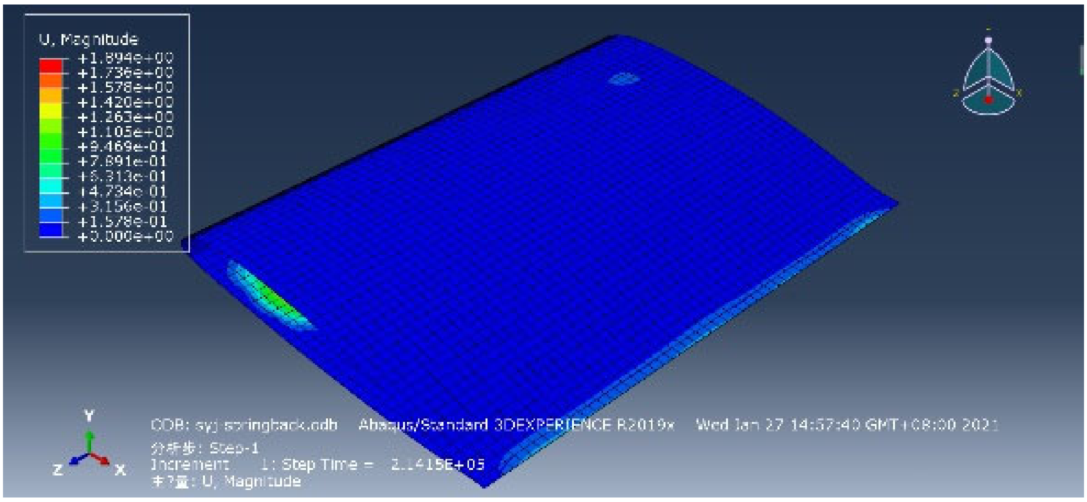


Figure 16. Deformation nephogram of composite part with the demolding temperature of 60 ℃

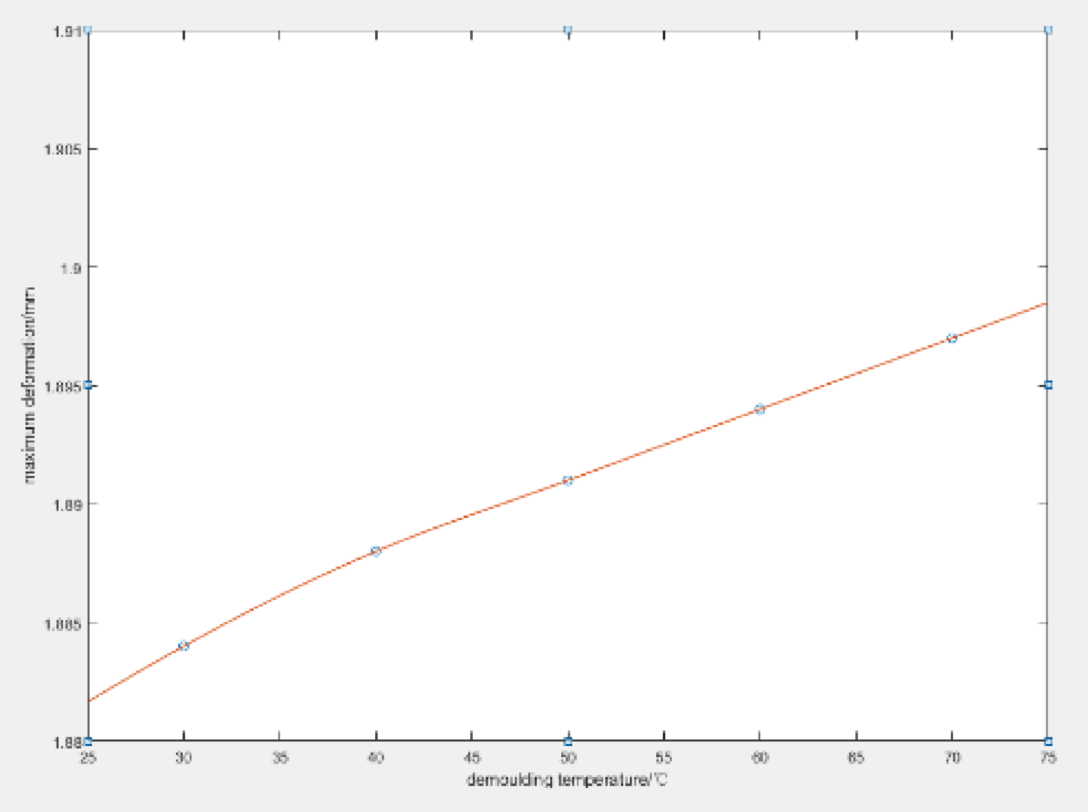
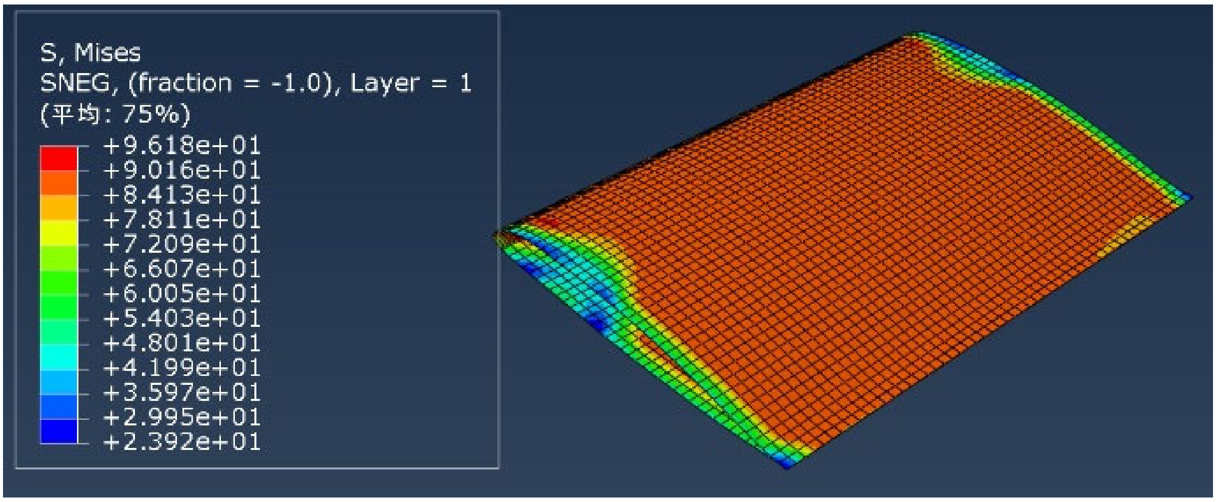
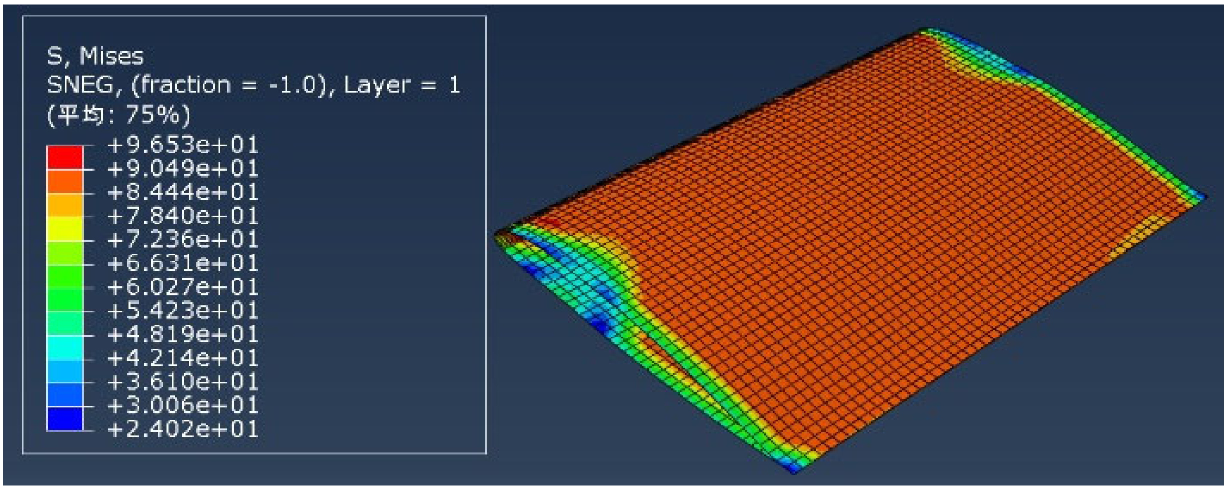


Figure 17. Comparison of simulation maximum deformation under different demolding temperatures

It can be found from the figure that the lower the demolding temperature is, the better the forming quality may be. When the demolding temperature is decreasing, the plasticity of the part increases and the deformation decreases after the mold constraint is released, thus the increasing function curve as shown in Figure 12 is obtained. Properly reducing the demolding temperature can reduce the spring-back deformation, but in the actual demolding process, if the demolding temperature is too low, the plasticity of the composite part will increase, resulting in the increase of internal stress, as shown in Figure 18, increasing the difficulty of demolding, demolding may cause some damage to the part, so the actual situation should be considered to reduce the demolding temperature.



(a)70°C



(b)30°C

Figure 18. Stress distribution nephogram under different demolding temperatures

5. CONCLUSION

In this paper, the influence mechanism of the temperature field on the precision of the part is analyzed through the thermochemical model, and the three main process parameters of heating rate, curing temperature and demolding temperature are mainly analyzed. By optimizing the simulation model of the verified composite part, the following conclusions are obtained.

Enlarging the curing temperature can increase the curing speed, but it will reduce the fluidity of prepreg and cause mold filling dissatisfaction. While the curing temperature is excessive low, it will cause a low degree of curing, resulting in the decline of precision, so the appropriate curing temperature is particularly important. The appropriate heating rate is conducive to heat exchange, heating fast will easily lead to uneven temperature distribution, which will increase the deformation of part. Heating slowly will decrease the curing efficiency and increase the cost. And the smaller demolding temperature can reduce the spring-back of composite parts.

Through the simulation and optimization of the process parameters of the simulation model, it can be concluded that: for the composite part molding process in this paper, the appropriate curing platform temperature range is 120 °C - 130 °C; the appropriate heating rate range is 1.47 °C / min - 1.52 °C / min; the demolding temperature should be reduced appropriately.

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