Numerical study on curing-induced residual stress and deformation of adhesively bonded sandwich structures of dissimilar materials

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Abstract
Adhesively bonded sandwich structure with dissimilar materials becomes an important means of lightweight for the next generation of autobody closure panels. However, during the baking process, the complicated change of physical properties of the adhesive can lead to structural mismatch deformation. In this paper, a multi-physics coupling numerical model of the curing process is proposed to reveal the deformation mechanism of adhesively bonded sandwich structures quantitatively. The material constitutive model of the one-component hemming adhesive hemming adhesive is established, considering evolution of curing properties. The curing process of typical aluminum alloy and steel-bonded sandwich structure is simulated in COMSOL Multiphysics. The predicted surface deformation of the component is verified by experiment using Digital Image Correlation (DIC) technique, which captures the full-field displacement in a non-intrusive manner. Then, the development process of surface deformation of the outer panel and residual internal stress of the adhesive layer is analyzed, and the influence of temperature cycle on the maximum deformation of the component is discussed. The results show that at the beginning of holding stage, the deformed component slightly rebounds, which is related to the chemical shrinkage. Mechanical strain caused by the coefficient of thermal expansion (CTE) and stiffness difference of the inner and outer panels is dominant in the adhesive layer. Reducing the curing rate and maximum holding temperature can reduce the overall deformation of the structure.

Keywords Dissimilar materials · Sandwich structures · Adhesively bonded · Multi-physics fields · Mismatch deformation · Curing induced

1 Introduction
Whether traditional fuel vehicles need to meet increasingly stringent environmental regulations or new energy vehicles continue to improve the endurance mileage, autobody lightweight is a common and key basic technology [1, 2]. The steel aluminum hybrid structure not only gives full play to the strength and manufacturing cost advantages of high-strength steel, but also takes into account the weight reduction and energy absorption characteristics of aluminum, and has become an effective way to lightweight the new generation of autobody [3]. Therefore, steel-aluminum hybrid closure panels with sandwich structure, such as doors, hoods, and deck lids, gradually become the focus of lightweight research.

The sandwich structure is composed of the hemming adhesive, the inner panel, and the outer panel, which are connected by the composite process of gluing, hemming, and baking [4]. In general, the research and application of similar material connection technology have been relatively mature [5]. However, when dissimilar materials are used due to the significant differences in the stiffness and CTE, large residual stress and warping deformation of the structure are generated in the baking condition [6, 7], which seriously affect the assembly accuracy and appearance perception quality of the closure panels. In order to restrain and eliminate the structure mismatch, it is necessary to understand the deformation mechanism.

Under baking cycle temperature load, the one-component adhesive gradually changes from viscous fluid to viscoelastic solid due to the internal molecular crosslinking reaction, and the physical properties also change. Meanwhile, the
adhesive and the panel are firmly connected at the bonding interface, resulting in complex mechanical interaction. Xin et al. [5] experimentally studied the dimensional changes of hood before and after curing, and pointed out that adjusting the heating mode and position can reduce the deformation. Andersson [8] concluded that the curing of adhesive can not only cause local deviation of gluing area, but also induce global deviation of appearance components. Fernholz et al. [9–11] studied the optical defects of bondline read-through by experiment, and found that the highest curing temperature was the primary factor, and the modulus, cross-sectional geometry, and thermal expansion characteristics of the adhesive also played a significant role on the final distortion. Thus, mastering the evolution of mechanical properties of adhesives is the key to reveal the structural deformation mechanism of dissimilar materials.

Compared with experiments, numerical simulation can effectively predict structural deformation and directly obtain internal stress state of adhesive layer, which has become an important research method. Due to the complex changes in the baking process, there is no uniform constitutive model for the adhesive. Basu and Kia [12] used the linear elastic model to simulate the adhesive and studied the bondline read-out, and indicated that the distortion was mainly due to the different thermal shrinkage between the adhesive and adherends. Patankar et al. [13] studied the curing deformation of bimaterial adhesive-metal, and discussed the stress relaxation during cooling stage using viscoelastic model. Fuchs et al. [14] indicated that the viscoelastic model had higher accuracy in predicting deformation than the linear model. Zhou et al. [15] simulated the curing process of aluminum-steel bonded joint using viscoelastic model, and concluded that the maximum deformation decreased with the increase of aluminum panel thickness. These models assumed that the structure was in stress-free state before cooling. However, experimental studies showed that many factors, such as heating rates [5], chemical shrinkage, and curing kinetics [10, 16], could also affect the final results. To improve the prediction accuracy of the hemming structure, it is necessary to establish a material model covering the whole curing cycle.

Since experiments show that the Poisson’s ratio of polymer materials varies greatly and it is related to curing degree and temperature [17, 18], the thermo-viscoelastic model [19, 20] assuming that Poisson’s ratio is constant is not suitable for adhesives. In order to more accurately reflect the change of mechanical properties and improve the calculation efficiency, vreugd [21] established the curing constitutive model of polymer materials by using bulk modulus and shear modulus, and studied the changes of material properties with temperature and curing degree. Konstantin et al. [22] ignored the properties of materials before gelation and established the curing constitutive models in heating, heat preservation, and cooling stages, respectively. These methods covering full curing cycle have been applied in coating process [23], resin mold material [18], and electronic packaging [24]. It provides a reference for the establishment of material constitutive model of the hemming adhesive.

In summary, the deformation mechanism of the adhesive-bonded sandwich structure of dissimilar materials in the baking process is not clear. It seriously limits the design and application of the new generation of material hybrid auto-body closure panels. In this study, a multi-physics coupling numerical model of one-component adhesive during the curing process is proposed. The material constitutive model of the hemming adhesive is established, considering evolution of curing properties. The curing process of typical aluminum alloy and steel-bonded sandwich structure is simulated in Comsol Multiphysics. The predicted transient surface deformation is verified by DIC measurement experiment. Then, the development of the internal stress of the adhesive and the deformation of the structure are analyzed, and the maximum deformation of the component under different temperature cycles is discussed.

## 2 Multi-physics field coupling model

### 2.1 Governing equations

During the baking process, the deformation process of sandwich structure is a coupling process of multi-physics fields involving heat transfer, material transformation, and structural mechanics. The heat convection occurs between the outer surface of the structure and the surrounding air, while the heat transfer occurs inside. The air temperature is heated from room temperature \( T_0 \) to the highest temperature \( T_b \) at a certain heating rate \( K_1 \). After holding for a period of time, the temperature drops to room temperature \( T_0 \) at a certain rate \( K_2 \). The partial differential equation of this transient heat transfer process is described as follows [25, 26]:

\[
\rho c \frac{dT}{dt} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + \rho H_a \frac{da}{dt} \tag{1}
\]

where \( \rho \) and \( c \) represent the density and specific heat of the material, respectively; \( k_i \) is the heat conductivity coefficient \( (i = x, y, z) \); \( T \) represents the temperature; \( \alpha \) and \( da/dt \) represent the curing degree and the instantaneous curing rate of the hemming adhesive, respectively; and \( H_a \) represents the total amount of heat released by the adhesive after curing reaction. The thermal convection boundary condition of the component is defined as follows:

\[
k_i \frac{dT}{dn} + h_{eff}(T_s - T_{ref}) = 0 \tag{2}
\]

where \( T_s \) is the temperature of the component surface, \( T_{ref} \) is the heating environment temperature, \( h_{eff} \) is the equivalent...
convection heat transfer coefficient of air, and its constant value is 25 W/m²·K.

The hemming adhesive of Type Dow 1496 V is a kind of one-component thermosetting resin adhesive commonly used in the autobody closure panels. Differential scanning calorimeter STA449C/3/G (Netzsch, Germany) is used to obtain the data in the curing process. The curing phase transition model of the hemming adhesive is an autocatalyotic Kamal-sourour model [27], which is obtained by Málek method [28]:

$$\frac{da}{dt} = Aa^m(1 - a)^n \exp\left[-\frac{E_a}{RT}\right]$$

(3)

where $R$ is the universal gas constant of 8.314 J/mol·K, $A$ is the exponential factor, $E_a$ is the reaction activation energy, and $m$ and $n$ are the reaction order, as shown in Table 1.

In the viscoelastic structure field, the bulk modulus and shear modulus can generally be used to establish the relationship between stress and strain [29]. The three-dimensional linear viscoelastic constitutive equation in integral form can be expressed as

$$\sigma_{ij} = \int_0^t \left[K(t - \tau) - \frac{2}{3}G(t - \tau)\right] \delta_{ij} \dot{\varepsilon}_{kk} d\tau + 2 \int_0^t G(t - \tau) \dot{\varepsilon}_{ij} d\tau$$

(4)

where $\sigma_{ij}$ is the Cauchy stress tensor, $\varepsilon_{ij}$ is the strain tensor, and $\delta_{ij}$ is the Kronecker symbol, $\varepsilon_{kk} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$. $G(t)$ and $K(t)$ represent the shear modulus and bulk modulus, respectively.

In the coupled physical field composed of Eqs. (1)–(4), elastic and thermal strains are mainly produced in the aluminum alloy and steel panel. In addition to the elastic, thermal, and chemical strains, the material stiffness of the adhesive will also change with the curing degree, temperature, and time.

2.2 Constitutive model of the hemming adhesive

In order to improve the prediction accuracy and reduce the testing and calculation time of complex parameters, a four-phase curing constitutive model of the hemming adhesive is established during the baking process based on the previous studies [18, 21–24], as shown in Fig. 1.

During the phase I, as the temperature is lower than the gel temperature $T_{gel}$, the adhesive can flow and relax rapidly under the action of external force [23]; thus, it can offset the changes in the movement of the panels. Therefore, the effect of mechanical properties in this phase can be ignored. When the temperature exceeds $T_{gel}$, the initial shear modulus is established, and the mechanical properties mainly occur in phases II, III, and IV. The total strain consists of three parts:

$$\varepsilon_{ij} = \varepsilon_{ij}^{ex} + \varepsilon_{ij}^{ch} + \varepsilon_{ij}^{th}$$

(5)

where $\varepsilon_{ij}^{ex}$ is the mechanical strain, $\varepsilon_{ij}^{ch}$ is the chemical strain, and $\varepsilon_{ij}^{th}$ is the thermal strain.

2.2.1 Phase II

Theoretically, the bulk modulus of the adhesive is related to the curing characteristics. However, when the curing degree changes, it is found that the bulk modulus of the hemming adhesive is almost unchanged, which is similar to other polymers [30]. Therefore, this model assumes that the bulk modulus only depends on the temperature. Based on the Tait equation, the modified bulk modulus is used in same way as in literature [21, 23]:

$$K(T) = \left[k_1s_0 + \frac{1}{2}k_2s_0(1 + \tanh(c_1(T - T_g)))\right] + \frac{C}{B(T)^{-1}}$$

(6)

$$B(T) = b_1 \exp(-b_2T)$$

(7)

Table 1 Main constitutive model parameters of the adhesive

| A (1/min) | E (kJ/mol) | m | n | $V_0$ (cm³/g) | $k_1$ (1/°C) | $k_2$ (1/°C) | $b_1$ (MPa) |
|----------|-----------|---|---|-------------|-------------|-------------|-------------|
| 5.89E10  | 91.62     | 0.61 | 1.72 | 0.8251 | 1.5E-4 | 2.7E-4 | 428.1 |
| $b_2$ (1/°C) | $c_1$ (1/°C) | $s_0$ (°C/MPa) | $q_{gel}$ | $T_g$ (°C) | $G_{inul}$ (MPa) | $K_{suf}$ (W/m·°C) | — |
| 0.01592 | 0.0224 | 3.34 | 0.45 | 88 ~ 91 | 58.3 | 0.2 | — |
where $s_0$, $b_1$, and $b_2$ are the fitted constants of the adhesive material. $C$ is the universal Tait constant, equal to 0.0894. The relationship between pressure–volume–temperature ($P–V–T$) [30, 31] is measured by high-pressure dilatometer PVT6000 (Gotech, China). According to the measurement method of literature [21], the relevant parameters are shown in Table 1.

The establishment of shear modulus starts from the gel point $T_{gel}$. During the heating and holding phase, a high elastic material function related to curing degree is used [17]:

$$G(\alpha) = G_{\text{final}} \left( \frac{\alpha^2 - \alpha_{gel}^2}{1 - \alpha_{gel}^2} \right)^\frac{1}{2}$$  

(8)

where $G_{\text{final}}$ is the shear modulus of the fully cured adhesive and $\alpha_{gel}$ is the curing degree of the adhesive at $T_{gel}$.

The thermal strain can be expressed as

$$\varepsilon_{ij}^{th} = CTE_{adh} \cdot (T - T_{ext})$$  

(9)

Theoretically, the CTE of adhesive is changing with pressure, temperature, and volume. Since the baking process is carried out at atmospheric pressure, it is independent of pressure. The CTE is modeled in the same way as in literature [21, 24]:

$$CTE_{adh} = k_1 + \frac{1}{2} k_2 (1 + \tanh[c_1(T - T_g)])$$  

(10)

Although the chemical shrinkage and thermal expansion strains coexist, studying them separately is helpful to understand the process of stress generation. Many scholars have adopted linear simplified models related to curing degree [32]:

$$\varepsilon_{ij}^{ch} = (\alpha - \alpha_{gel}) \varepsilon_{max}^{ch}$$  

(11)

where $\varepsilon_{max}^{ch}$ is the volume chemical shrinkage from the gel point to fully cured state.

### 2.2.2 Phases III and IV

During the cooling phases III and IV, the adhesive has been completely cured, and the chemical shrinkage has stopped. The model of bulk modulus is the same as the Eqs. (6) and (7), and the model of CTE is the same as Eq. (10). A linear viscoelastic relaxation function is used for the fully cured shear modulus [24]:

$$G(t) = G_\infty + \sum_{m=1}^{N} G_m \exp(-t/\tau_m)$$  

(12)

The deviator stress and strain can be expressed as follows:

$$\sigma_{ij}^{dev} = 2G_\infty \varepsilon_{ij}^{dev} + 2 \sum_{m=1}^{N} G_m q_m$$  

(13)

where $G_\infty$ is the equilibrium modulus and $G_m$ and $\tau_m$ are the relaxation modulus and relaxation time of the $m$-th Maxwell unit, respectively. The stress relaxation parameters of the hemming adhesive are obtained by torsional test system MTS809 with temperature chamber (MTS, USA). According to the measurement method of literature [21], the fitted ten-order main shear relaxation modulus spectrum is shown in Table 2.

The mechanical relationship between any point and the reference temperature point can be established by using the time–temperature equivalent equation. The difference between phase III and phase IV is that different time temperature equivalent equations are used. In phase III, WLF equation [21] is used for the region above the glass transition temperature. In phase IV, Arrhenius equation [33] is applied to the region of secondary transition temperature:

$$\log \alpha_r = \begin{cases} \frac{C_1(T - T_{ref})}{(\frac{T}{T_g})^{C_2} - \frac{1}{T_g}} & T > T_{ref} \\ \frac{C_1(T - T_{ref})}{(\frac{T}{T_g})^{C_2} - \frac{1}{T_g}} + 100 & T < T_{ref} \end{cases}$$  

(14)

where $T_{ref}$ is the reference temperature and $T_g$ is the glass transition temperature. The constant $C_1$ is 17.44 and $C_2$ is 51.6.

### 2.3 Material model of metal sheet

The material of outer panel studied is aluminum alloy AA6016-T4, which has good mechanical and bending characteristics, and is widely used in automobile outer panels. The inner panel material is cold-rolled steel DC04, and the main parameters are shown in Table 3. During the process of curing, as there is no plastic deformation, the linear thermoelastic constitutive model is used.

### 3 Simulation and experiment

#### 3.1 Numerical simulation

A typical flat surface-straight edge panel [4] is taken as the research object, and the aluminum alloy and steel-bonded

| $G_{\infty}$ (GPa) | $G_1$ (GPa) | $G_2$ (GPa) | $G_3$ (GPa) | $G_4$ (GPa) | $G_5$ (GPa) | $G_6$ (GPa) | $G_7$ (GPa) | $G_8$ (GPa) | $G_9$ (GPa) | $G_{10}$ (GPa) |
|-------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|----------------|
| 100.4             | 28.3        | 29.3        | 37.9        | 28.4        | 27.9        | 46.7        | 89.3        | 79.4        | 94.6        | 66.4           |
| $\tau_0$ (h)      | $\tau_1$ (h) | $\tau_2$ (h) | $\tau_3$ (h) | $\tau_4$ (h) | $\tau_5$ (h) | $\tau_6$ (h) | $\tau_7$ (h) | $\tau_8$ (h) | $\tau_9$ (h) | $\tau_{10}$ (h) |
| 2.1E3             | 2.4E10      | 5.2E3       | 7.2E3       | 2.4E3       | 2.5E6       | 1.8E4       | 2.2E3       | 4.3E8       | 5.6E9       |                |

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sandwich structure is shown in Fig. 2. The thickness of aluminum alloy panel, steel panel, and upper/lower adhesive layer are 0.8 mm, 0.8 mm, and 0.2 mm, respectively, and the total component thickness is 2.8 mm. One end of the end is unrestrained and the other is fixed. According to the requirements of the autobody baking process [3], the component is cured and connected by thermal convection between the structure surface and the surrounding air. A curing temperature cycle of heating and cooling 4 K/min, maximum temperature 170 °C, and holding time 30 min is adopted, in accordance with the material characteristics of the hemming adhesive.

The thermal-chemical-structural coupling numerical model of the curing process is implemented and simulated in finite element analysis software (Version 5.5) COMSOL Multiphysics, which is suitable for solving coupling problems of multi-physical field. The modules of Heat Transfer, Partial Differential Equation (PDE), and Solid Mechanics are used to describe the physical fields of heat convection and transfer, adhesive curing, and structural deformation, respectively. The direct coupling between modules is realized by sharing the temperature and time variables, and the calculation of the numerical model can be achieved by calling the corresponding application module subroutine. The calculation flow of thermal-chemical-structural coupling field of bonded sandwich structure is shown in Fig. 3. In the Heat Transfer module, the boundary condition parameters of the model can be set, and the parameters (Tables 1 and 3) related to heat convection and heat transfer of different materials can be defined. In the PDE module, the general form of coefficient partial differential equation is

\[
e_u \frac{\partial^2 u}{\partial t^2} + d_u \frac{\partial u}{\partial t} + \nabla \cdot (-c \nabla u - au + \gamma) + \beta \cdot \nabla u + au = f
\]

where \(u\) and \(t\) are the dependent variable and time, respectively; \(f\) is the source form; and \(c, a, e, d, \alpha, \beta, \) and \(\gamma\) are the undetermined coefficients. By modifying the coefficients and the source term parameters (Table 1), formula (15) is transformed into the curing kinetics (Eq. (3)). In the Solid Mechanics module, the mechanical material parameters (Tables 1 and 3) of different materials, such as bulk modulus, shear modulus, and relaxation time (Table 2), can be defined.

The adhesive at the corner is divided into a triangular prism mesh with a minimum size of 0.05 mm, and the rest of the structure is divided into a hexahedral mesh as shown in Fig. 4. Along the \(x\) direction, the mesh of the structure is evenly divided, with the size of 2 mm. Along the \(y\) direction, the mesh size at the flanged part is relatively dense, which is 0.5 mm, while the mesh in other areas is relatively sparse. To improve the calculation accuracy, the quadratic Lagrangian element is used. In the temperature field, the air convection boundary condition is applied to the surface of the structure. In the structural field, the ends of the structure are fixed and other regions are unconstrained. Corresponding to the multi-stages of the constitutive model, the numerical calculation is also carried out in multi-stages and the transient time domain method is used.

### 3.2 Verification experiment based on DIC

In the baking environment, the adhesive layer is sandwiched between the inner and outer panels. As the deformation is dynamic, it increases the difficulty of direct gauging. When traditional strain gauge is used to measure the strain data of the adhesive layer in contact, the deformation accuracy of the sample is easily affected. Thus, indirect quantification of non-contact measurement becomes the best verification method [14]. To avoid the limitations of single-point
position measurement and record the full-field dynamic deformation of aluminum alloy outer panel, the DIC method is adopted, which is widely used in the deformation field of non-contact measurement [34].

The experimental principle and device are shown in Fig. 5. The measurement system mainly includes DIC device XTDIC (XTOP, China), oven, and high-temperature sensor. The cameras of the measurement device have 10 million pixels and the dynamic displacement identification accuracy of the system is 0.05 mm. The outer surface of the specimen is sprayed with speckle paint for system identification. The 0.2-mm steel block is placed in the middle of the sample end to control the thickness of the adhesive layer, as shown in Fig. 5a. Meanwhile, the length of the sample in the experiment is 10 mm longer than that of the simulation, and the extra 10 mm is used for clamping. Then, the sample is fixed by fixture, and placed on the refractory brick in the oven. The heating temperature cycle which is described...
in Sect. 3.1 is controlled by the oven, and the deformation results are recorded by the cameras. Finally, the data are compared and analyzed by DIC system. Each experiment is conducted three times and the average value is taken.

4 Results and discussion

4.1 Comparison of methods

For the convenience of comparison, the beginning of temperature cooling is defined as initial point \((t = 0 \text{ min})\) by time equivalent conversion. Since surface quality is the focus of the sandwich structure, Fig. 6 shows the curing-induced deformation values of the surface in the \(z\) direction (Fig. 4). It can be seen that the surface displacement values obtained by the experiment and the simulation are basically consistent, and the deformation trend is in good agreement. Because the width value is small, the deformation of the aluminum alloy panel changes little along the \(y\) direction. Therefore, when the length–width ratio is relatively large, the deformation of the sandwich structure is approximately regarded as a plane strain problem. In general, under the temperature cycle, the component first bends along the

![Fig. 5](image)

**Fig. 5** Curing-induced distortion measurement experiment. **a** Non-invasive measurement schematic diagram. **b** Measurement device based on DIC technology

![Fig. 6](image)

**Fig. 6** Evolution of curing-induced surface deformation of bonded sandwich structure in different temperature stages. **a** Measured by DIC experiment (one of the samples). **b** Simulation based on multi-field coupling model
negative direction of the $z$-axis, then gradually stabilizes, and finally bends in the positive direction of the $z$-axis. The results show that the deformation process can be simulated well based on the multi-physics coupling model.

As the deformation value is the largest and can reflect the degree of the structural deformation, the M-point (Fig. 2) on the middle section is selected as the comparison point. Figure 7a shows the transient variation process of M-point on the middle section obtained by using different methods. It can be seen that the curing-induced structural displacement does not occur at the beginning of heating. When the molecular crosslinking reaches a certain degree, M-point begins to move in the negative direction of the $z$-axis. After reaching the holding temperature, the deformation begins to rebound slightly, and then enters a stable state, which is related to the curing shrinkage. Finally, with temperature cooling down, the point begins to warp in the positive direction of the $z$-axis.

At the beginning of the cooling stage, the deformation speed of the structure is relatively slower, which is related to the faster stress relaxation of the adhesive. Figure 7b shows the final $z$-axis displacement of the outer contour of the middle section. It can be seen that the traditional viscoelastic models [12, 14] have a relatively large deviation from the experimental results, which ignores the change of material properties. The multi-physics coupled model well reflect the changing process.

### 4.2 Deformation process of the sandwich structure

Figure 8 shows the physical fields of the adhesive at different curing stages. It can be seen that the temperature almost does not change along the $x$ direction. In the heating stage, the temperature at the corner is slightly lower than that in other regions along the $y$ direction, which is related to the heat transfer. In the high holding stage, the temperature is about $1 \sim 2{\degree}C$ higher at the corner than that in other regions, which is related to the exothermic of the adhesive. In the heating and holding stage, the curing field is similar to the temperature field, and the difference is relatively small in different areas. In the structural field, the von Mises stress on both sides is relatively large, especially in the cooling stage, which is mainly related to the boundary constraints.

Figure 9 shows the development of temperature and curing degree distribution of the adhesive layer in the $y$–$z$ plane. It can be seen that the maximum temperature difference of the adhesive layer in different regions is about $1 \sim 2{\degree}C$. This is due to the high thermal conductivity of the panels and the relatively thin thickness of the adhesive layer, which results in no delaying and obvious gradient change. After heating up, the temperature continued to rise slightly due to the exothermic reaction of the adhesive. Accordingly, under the same external temperature environment, the change of the curing degree of each position has almost the same.

Figure 10 shows the evolution of different strains $\varepsilon_{zz}$ in $z$ direction at point $U_m$ (Fig. 2) of adhesive layer. When the temperature exceeds $T_{gel}$, the bonding strength at the interface is gradually established between the adhesive and the panels. Since the CTE of aluminum alloy is larger than that of steel, relative dislocation movement occurs [7]. Compared with other structures, such as bimaterial [13] and bonded substructure [14], mechanical strain caused by the difference of material properties plays an important role. At the beginning of the phase II, the influence of thermal expansion strain and mechanical strain on deformation is greater than that of chemical shrinkage. After reaching the maximum temperature $170{\degree}C$, the structure produces a small amount of positive movement along the $z$-axis, which can be explained by continuous curing shrinkage [16], as shown in Fig. 8. In the phase III, the chemical shrinkage gradually stops and remains unchanged. And compared with thermal strain, mechanical strain began to dominate, which cause the structure bend forward along the $z$-axis. In the phase IV, the mechanical strain decreases gradually due to the increase of the adhesive modulus.
Figure 11a shows development of internal stress of the adhesive layer at point $U_m$ (Fig. 2) on the middle section. It can be seen that the internal stress direction of point $U_m$, including tensile stress $\sigma_{xx}$, shear stress $\sigma_{xy}$, and peel stress $\sigma_{zz}$, changes with the decrease of the temperature. It shows that the upper adhesive layer is compressed first and then stretched. In phase II of the material constitutive model, due to the relatively low modulus, about tens of MPa, the internal stress value is relatively low. At the beginning of phase III, the stress grows slowly with the cooling of temperature, since the stress relaxation is fast, and the stress increases rapidly with the glass transition of the adhesive. In the phase IV, the stress increases slowly, which is related to the decrease of CTE and stress relaxation. Figure 11b shows the final internal stress at the middle line of the upper adhesive layer. The tensile and peel stress are slightly larger at the edge, which is related to the boundary constraint. The shear stress direction of the left side and the right side changes, which is related to the asymmetric structure.

Figure 12a shows development of internal stress of the adhesive layer at point $D_m$ on the middle section. The variation of point $D_m$ is similar to that of point $U_m$. Figure 12b shows the final internal stress at the middle line of the lower adhesive layer. The stress near the circular corner is relatively large, which is related to the geometric structure.

Figure 13 shows the final internal stress at the circular corner. It can be seen that the internal stress changes dramatically, and the stress concentration appears in the right
the heating rate exceeds a certain value, as the 8 K/min, the adhesive is bonded to the panels in the heat holding stage, and the overall deformation value is the maximum [9–11].

Figure 15a shows the maximum displacement of the outer panel at 150 °C under different heating rates. It can be seen that the final deformation at 150 °C is significantly lower than that at 170 °C. This is because the decrease of the maximum temperature reduces the gel temperature of adhesive, and reduces the temperature difference of cold contraction deformation between aluminum alloy and steel panels. Under the condition of 3, 4, and 8 K/min, the deformation value is almost the same, which is related to gel in the holding stage, as shown in Fig. 15b. The curing curve moves to the right, compared with the temperature condition of 170 °C. This makes the samples under the condition of 3, 4, and 8 K/min all gel and cure during the holding stage. When dissimilar materials are used, deformation always exists due to the difference of their material properties. Adjusting the curing kinetics characteristics of the adhesive layer can reduce the structural deformation, but it may prolong the curing time.

4.3 Influence of curing temperature cycles

Figure 14a shows the maximum displacement of the outer panel at 170 °C under different heating rates. It can be seen that the predicted value of the model is still in good agreement with the experimental results, when the heating conditions change. The results show that the final deformation of the structure can be reduced by reducing the curing rate. This is because that the heating rate affects the gel point and the bonding temperature between the adhesive and the panels [16]. Figure 14b shows the curing degree curves of the adhesive under different heating rates. When the heating rate decreases, the curing curve moves to the left, which leads to lower gel temperature. On the contrary, the higher the heating rate is, the higher the gel temperature reaches. When angle region, due to the change of boundary conditions. The tensile and shear stresses at the circular corner are less than those at the upper and lower adhesive layers. The shear stress decreases obviously and becomes zero in the middle region.

Fig. 9 Evolution of temperature and curing degree of the adhesive layer

Fig. 10 Evolution of strain at point $U_m$ under temperature cycle

Fig. 11 Variation of internal stress of the upper adhesive layer on the middle section. a Variation of different stresses at point $U_m$. b Final internal stress at the middle line
Fig. 12 Variation of internal stress of the upper adhesive layer on middle section. a Variation of different stresses at point $U_m$. b Final internal stress at middle line.

Fig. 13 Final internal stress at the circular corner. a Tensile stress. b Shear stress. c Peel stress.

Fig. 14 Maximum displacement and curing degree curves at holding temperature 170 °C. a Maximum displacement under different heating rates. b Curing degree curves.

Fig. 15 Maximum displacement and curing degree curves at holding temperature 150 °C. a Maximum displacement under different heating rates. b Curing degree curves.
5 Conclusion

A multi-physics coupling numerical model of the curing process was proposed to study the residual internal stress and deformation of the adhesively bonded sandwich structure of dissimilar materials. The simulation prediction accuracy is verified by experiments. Then, the development process of surface deformation of the outer panel and internal stress of the adhesive layer is analyzed, and the influence of temperature cycle on the maximum deformation of the component is discussed. Several conclusions can be drawn:

1. Compared with the traditional viscoelastic model, the multi-physics coupled model has higher prediction accuracy and can better reflect the deformation process of the structure due to considering the change of adhesive material properties.

2. At the beginning of the holding stage, the deformed component slightly rebounds, which is related to the chemical shrinkage. At the beginning of the cooling stage, the deformation rate is relatively slow, which is related to the faster stress relaxation of the adhesive.

3. The temperature difference in different areas of the adhesive layer is relatively small, about 1–2 °C, and the difference of the curing degree is less than 0.01, due to the high thermal conductivity of the panels and the thin thickness of the adhesive layer.

4. Compared with other structures, such as bimaterial [13] and bonded substructure [22], mechanical strain caused by the CTE and stiffness difference of inner and outer panels is dominant. The direction and size of shear stress in the upper and lower adhesive layers change along the y-axis, which is related to asymmetric structure.

5. When the gel temperature is the maximum holding temperature, the overall deformation reaches the maximum. Reducing the curing rate and maximum holding temperature is helpful to reduce the overall deformation, as it reduces the gel temperature of the components.

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Declarations

Conflict of interest The authors declare no competing interests.

References

1. Martinsen K, Hu S, Carlson B (2015) Joining of dissimilar materials. CIRP Ann-Manuf Technol 62(5):679–699. https://doi.org/10.1016/j.cirp.2015.05.006

2. Baneea M, Rosioarb M, Carbasa B, Silva L (2018) Multi-material adhesive joints for automotive industry. Composites Part B-Eng 151:71–77. https://doi.org/10.1016/j.compositesb.2018.06.009

3. Hu P, Han X, Li W, Shi Z, Zhou S (2012) Influence of automobile body coating process on the strength of unbalanced adhesive joints. Chin J Mech Eng 48(20):93–102. https://doi.org/10.3901/JME.2012.20.093

4. Hu X, Zhao Y, Huang S, Li S, Lin Z (2012) Numerical analysis of the roller hemming process. Int J Adv Manuf Technol 62(5–8):543–550. https://doi.org/10.1007/s00170-011-3822-4

5. Xin W, Hao H, Zhang G, Cindy R (1999) Variation in autobody adhesive curing process. International Congress and Exposition Detroit, Michigan, 01-0997. https://doi.org/10.4271/1999-01-0997

6. Zhu X, Li Y, Chen G, Wang P (2013) Curing-induced distortion mechanism in adhesive bonding of aluminum aat6061-t6 and steels. J Manuf Sci E-T ASME 135:051007. https://doi.org/10.1115/1.4025013

7. Silva L, Adams R (2007) Adhesive joints at high and low temperatures using similar and dissimilar adherends and dual adhesives. Int J Adhes Adhes 27:216–226. https://doi.org/10.1016/j.ijadhadh.2006.04.002

8. Andersson A (2009) Evaluation and visualisation of surface defects on auto-body panels. J Mater Process Tech 209:821–837. https://doi.org/10.1016/j.jmatprotec.2008.02.078

9. Fernholz K, Blair B, Wang C, Lazarz K (2008) Bond-line read-through investigation for composite closure panels: initial doe results. SPE Automotive Composites Conference, Troy, MI

10. Fernholz K, Lazarz K, Wang C (2009) Preliminary results from an experimental evaluation of the root causes of bond-line read-through. The Adhesion Society 32nd Annual Meeting, Savannah, GA, pp 285–287

11. Fernholz K, Lazarz K (2010) Effect of cure temperature on the severity of bond-line read-through induced surface distortion. The Adhesion Society 33rd Annual Meeting, Daytona Beach, FL, pp 211–213

12. Basu S, Kia H (2008) Theoretical modeling of bond-line read-out in adhesive joined SMC automotive body panels. J Compos Mater 42:539–552. https://doi.org/10.1177/0021998307088604

13. Patankar K, Dillard D, Fernholz K (2013) Characterizing the constitutive properties and developing a stress model for adhesive bond-line readout. Int J Adhes Adhes 40:149–157. https://doi.org/10.1016/j.ijadhadh.2012.07.006

14. Fuchs H, Fernholz K, Deslauriers P (2010) Predicted and measured bond-line read-through response in composite automotive body panels subjected to elevated temperature cure. J Adhesion 86:982–1011. https://doi.org/10.1080/00032740.2010.515471

15. Zhou L, Lin G, Jack S (2008) Modeling of curing-induced distortion of adhesive-bonded joints. Proceedings of the 8th Sheet Metal Welding Conference, Sheet Metal Welding Conference XIII, Livonia, MI

16. Konstantin P, Jos S, Rinze B (2014) Influence of the temperature cycle on local distortions in car panels caused by hot curing epoxies. Int J Adhes Adhes 50:216–222. https://doi.org/10.1016/j.ijadhadh.2014.01.035
17. Adolf D, Martin J (1996) Calculation of stresses in crosslinking polymers. J Compos Mater 30:13–34. https://doi.org/10.1177/002199839603000102

18. Kiasat M (2000) Curing shrinkage and residual stresses in viscoelastic thermosetting resins and composites, Doctoral dissertation, Delft University of Technology

19. Eom Y, Boogh L (2000) Time-cure-temperature superposition for the prediction of instantaneous viscoelastic properties during cure. Polym Eng Sci 40:1281–1291. https://doi.org/10.1002/peng.11256

20. Ding A, Li S, Sun J, Wang J, Zu L (2016) A thermo-viscoelastic model of process-induced residual stresses in composite structures with considering thermal dependence. Compos Struct 136:34–43. https://doi.org/10.1016/j.composites.2015.09.014

21. Vreugd J (2011) The effect of aging on molding compound properties. Doctoral dissertation, Delft University of Technology

22. Konstantin P, Jos S, Rinze B (2014) On the simulation of panel distortions due to hot curing adhesives. Int J Solids Struct 51:2470–2478. https://doi.org/10.1016/j.ijsolstr.2014.03.016

23. Jansen K, Vreugd J, Ernst L (2012) Analytical Estimate for curing-induced stress and warpage in coating layers. J Appl Polym Sci 126:1623–1630. https://doi.org/10.1002/app.36776

24. Vreugd J, Jansen K, Ernst L, Bohm C (2010) Prediction of cure induced warpage of micro-electronic products. Microelectron Reliab 50(7):910–916. https://doi.org/10.1016/j.microrel.2010.02.028

25. Yan X (2010) Finite element modeling of curing of epoxy matrix composites. J Appl Polym Sci 103(4):2310–2319. https://doi.org/10.1002/app.24337

26. Li D, Li X, Dai J (2018) Process modelling of curing process-induced internal stress and deformation of composite laminate structure with elastic and viscoelastic models. Appl Compos Mater 25:527–544. https://doi.org/10.1007/s10443-017-9633-5

27. Kissing H (1957) Reaction kinetics in differential thermal analysis. Anal Chem 29:1702–1706. https://doi.org/10.1021/ac60131a045

28. Málek J (1992) The kinetic analysis of non-isothermal data. Thermochim Acta 200:257–269. https://doi.org/10.1016/0040-6031(92)85118-F

29. Ernst L, Hof C, Yang D, Kiasat M, Zhang G, Bressers H, Caers J, Boer A, Janssen J (2002) Mechanical modeling and characterization of the curing process of underfill materials. J Electron Packaging 124:97–105. https://doi.org/10.1115/1.1459471

30. Yang D, Jansen K, Ernst L, Zhang G, Janssen J (2007) Effect of filler concentration of rubbery shear and bulk modulus of molding compounds. Microelectron Reliab 47:233–239. https://doi.org/10.1016/j.microrel.2006.09.031

31. Li Y, Mahmood S, Park C (2016) Visualization for measuring the PVT property of viscoelastic polystyrene/CO₂ mixtures at elevated temperatures and pressures. Polym Test 55:88–96. https://doi.org/10.1016/j.polymertesting.2016.08.010

32. Zarrell M, Skordo A, Partridge I (2002) Investigation of cure induced shrinkage in unreinforced epoxy resin. Plast Rubber Compos 31:377–384. https://doi.org/10.1179/146580102225006350

33. Senum G, Yang R (1977) Rational approximations of the integral of the Arrhenius function. J Therm Anal Calorim 11:445–447. https://doi.org/10.1007/BF01903696

34. Ke L, Li C, He J, Dong S, Chen C, Jiao Y (2020) Effects of elevated temperatures on mechanical behavior of epoxy adhesives and CFRP-steel hybrid joints. Compos Struct 235:111789. https://doi.org/10.1016/j.composites.2019.111789

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