IOP Conference Series: Materials Science and Engineering

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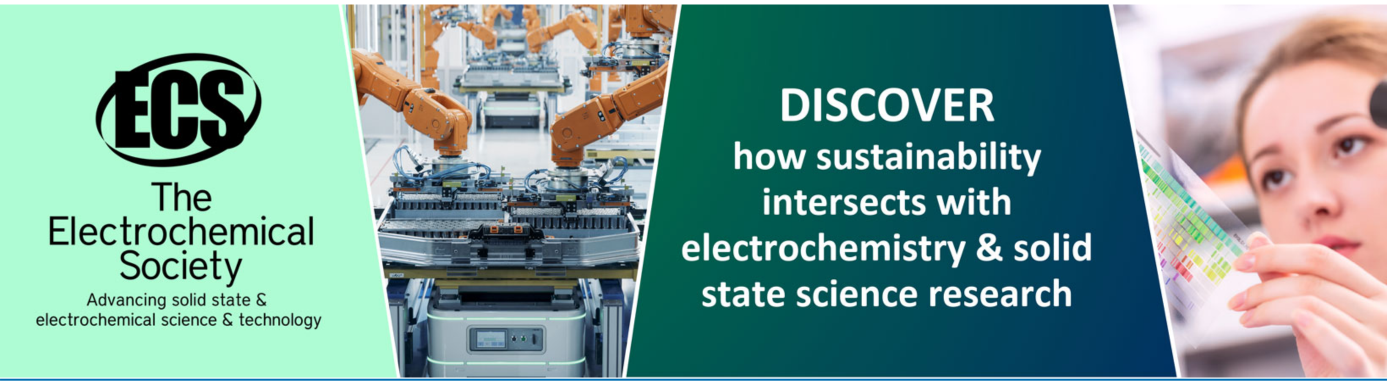
To cite this article: C L Guan *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **474** 012056



IOP Conf. Series: Materials Science and Engineering 474 (2019) 012056 doi:10.1088/1757-899X/474/1/012056

The composite curing deformation prediction with the account of mold factors

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Abstract: In this paper, the effect of interaction on the curing deformation of resin matrix composite materials were investigated through introducing a shear layer to identify the interaction between the mold and the component, and a numerical calculation model was established between the parameter and the maximum deformation. Then, the experimental data in the existing literature was compared with numerical calculation model data to verify the accuracy of the calculation model. The results of numerical model proved that the curing deformation does not have a direct relationship to the shear modulus and the thickness of the shear layer, but only to the ratio of the shear modulus to the thickness. The experimental results show that the calculation model hardly changes with the transformation of the length of the components, but varies with the ply of the laminates. When comparing the curing deformation obtained by calculation model with the deformation measured by experiment, it can be concluded that the model can predict the curing deformation of composite laminates with different length and thickness. Taking the practical significance into consideration, the introducing of ratio parameter can reflect the influence of the mold on the curing deformation of the components more concise. The numerical model between the parameters and the maximum deformation is established based on the shear layer, which can predict the curing deformation of the laminates with different lengths and thicknesses more accurately.

1. Introduction

Since the coefficient of thermal expansion of the metal mold is much larger than that of the composites, there is a mismatching in the process of heat deformation during the curing process of autoclave molding. Hence, under the action of large pressure, the bottom layer of the components is tightly fitted on the upper surface of the mold. Due to the inconsistent amount of heat deformation, shear stress will occur between the mold and the material, the shear force generated can be transmitted to the respective layers through the resin during the viscoelastic phase. However, at this stage, the modulus of the resin matrix is still relatively small, the interaction cannot be well transferred, resulting in a stress gradient in the thickness direction. That stress will remain interiorly after curing cycle, which will be released after demoulding and will lead to the curing deformation. [1-2]

To date, a great number of papers have been published on the effect of the mold during the curing of composites. Twigg *et al.* [3-4] found that the component and the mold are neither completely slipped nor stationary during the viscoelastic stage. Bapanapalli *et al.* [5] introduced a shear layer into the model to study the interaction between mold and component. By changing the parameters of the shear layer, the simulated values close to the experimental values were obtained, so then the shear layer parameters under specific materials, mold and pressures were also determined. This method can accurately predict the solidification deformation caused by the action of the mold, but the shear layer parameters need to be redefined in different processes and structures. Arafath *et al.* [6] introduced a shear layer to express the interaction between the mold and composite layer which shows that the curing deformation of composites depends on the choice of the elastic modulus of the resin matrix. Zeng *et al.* [7] used the friction theory to establish three-dimensional curing model of large aeronautical structural components and the warpage deformation of which was predicted based on commercial finite element software. The accuracy of this three-dimensional model was also verified by experiments.

Yue *et al.* [8-10] studied the mold action in the curing process by embedding fiber grating in the composite components and established a finite element model to predict the deformation based on the shear layer. Yuan *et al.* [11] established a finite element model to predict curing deformation using aof shear layer method. The three-dimensional simulation model of L-type composites was established taking into account the mold factors, which shows that the prediction of curing deformation is more accurate after considering the action of mold.

This paper also introduces a shear layer to identify the interaction between mold and component. Most of the previous studies have obtained specific shear layer performance parameters with the complicated calculation. In this paper, a ratio parameter λ is used to reflect the influence of the mold on the curing deformation of the components, which is more concise. The numerical model between the parameters and the maximum deformation is established based on the shear layer, which is proved to more accurately predict the curing deformation of the laminates with different lengths and thicknesses.

2. A calculation Model between warpage deformation and Shear layer

The shear layer, as the medium of force transfer, is similar to the black box identification method. It is assumed that the introduced shear layer is located on the upper surface of the mold and the bottom layer of the composite component. When the temperature rises, the interaction between the mold and the component is produced through the shear layer. The relationship between the mold and the shear layers and the components is shown in figure 1.

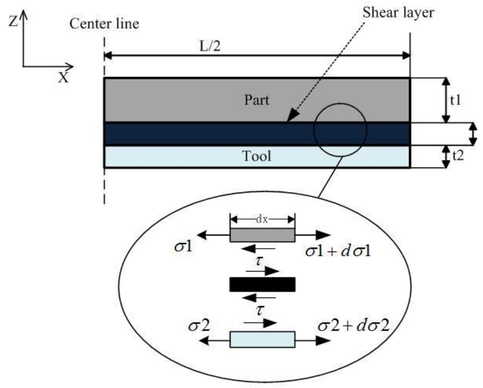

Figure 1. Sketch of X coordinate direction.

Due to the mismatch of the thermal expansion coefficient between the mold and the material during the curing process, the interface between themis interacts. Assuming this interaction isa shear stress, which can be determined as:

$$\tau = \frac{\mathrm{d}\sigma_1}{\mathrm{d}x} \cdot t1 = -\frac{\mathrm{d}\sigma_2}{\mathrm{d}x} \cdot t2 \tag{1}$$

where σ_1 and σ_2 are the stresses of the component and the mold respectively; $t1$ and $t2$ are the thickness of the component and the mold.

According to Hooke's law:

$$\frac{\mathrm{d}u_1}{\mathrm{d}x} = \frac{\sigma_1}{E_1} + \alpha_{1,j} \cdot \Delta T \tag{2}$$

$$\frac{\mathrm{d}u_2}{\mathrm{d}x} = \frac{\sigma_2}{E_T} + \alpha_T \cdot \Delta T \tag{3}$$

where u_1 and u_2 are the displacements of the component and the mold in the X direction respectively during the curing process; $\alpha_{1,j}$ is the coefficient of thermal expansion of the component in the X direction; α_T is the coefficient of thermal expansion of the mold.

For the shear layer, the shear force can be described as:

$$\tau = G \cdot \gamma = G \cdot \frac{u_1 - u_2}{t} \tag{4}$$

where G is the shear modulus of the shear layer and t is the thickness of the shear layer.

From equations (1) - (4), we get:

$$\frac{\mathrm{d}^2\tau}{\mathrm{d}x^2}=\tau\cdot\eta \tag{5}$$

where $\eta=\dfrac{G(E_1\cdot t1+E_T\cdot t2)}{t\cdot E_1\cdot E_T\cdot t1\cdot t2}$.

From figure 1, the boundary conditions can be expressed as:

$$\tau(0)=0;\sigma_1(L/2)=\sigma_2(L/2)=0 \tag{6}$$

where L is the length of the component.

From the above equations:

$$\tau=k\cdot[\exp(\eta^{\frac{1}{2}}x)-\exp(-\eta^{\frac{1}{2}}x)] \tag{7}$$

Where $k=\dfrac{G\cdot(\alpha_{1,j}-\alpha_T)\cdot\Delta T}{t\cdot\eta^{\frac{1}{2}}\cdot[\exp(\eta^{\frac{1}{2}}\cdot L/2)+\exp(-\eta^{\frac{1}{2}}\cdot L/2)]}$.

From equation (1):

$$\sigma_1=\int_0^{L/2}\frac{\tau}{t1}\mathrm{d}x \tag{8}$$

The bending moment caused by the stress obtained by equation (8) can be expressed as:

$$M=\int_0^{t1}\sigma_1\cdot b\cdot(z-\frac{t_0}{2})\mathrm{d}z \tag{9}$$

where b is the width of the laminate and t_0 is the thickness of the single layer of the material. According to the knowledge of material mechanics, the maximum deformation of the laminate which under the action of bending moment M can be expressed as:

$$v_{\max}=\frac{M}{2E_1I}(L/2)^2 \tag{10}$$

where a cross-sectional moment of inertia $I=(b\cdot t1^3)/12$. It can be calculated from equation (7)-(10) that:

$$v_{\max}=k_1\cdot\frac{3(\alpha_{1,j}-\alpha_T)\cdot\Delta T\cdot(t1-t_0)\cdot L^2}{2\cdot t1^3\cdot E_1} \tag{11}$$

where $k_1=\dfrac{G\cdot[\exp(\eta^{\frac{1}{2}}\cdot L/2)+\exp(-\eta^{\frac{1}{2}}\cdot L/2)-2]}{t\cdot\eta\cdot[\exp(\eta^{\frac{1}{2}}\cdot L/2)+\exp(-\eta^{\frac{1}{2}}\cdot L/2)]}$ is a fixed value.

The shear layer parameter λ and the parameter λ_1 which is related to the thickness and the modulus of elasticity of the component and the mold are introduced. Let $\lambda = \frac{G}{t}$, $\lambda_1 = \frac{E_1 \cdot t1 + E_T \cdot t2}{E_1 \cdot E_T \cdot t1 \cdot t2}$, and λ_1 is a fixed value, then k_1 can be expressed as:

$$k_1 = \frac{1}{\lambda_1}(1 - \frac{2}{\exp(L \cdot \lambda^{\frac{1}{2}} \cdot \lambda_1^{\frac{1}{2}} / 2) + \exp(-L \cdot \lambda^{\frac{1}{2}} \cdot \lambda_1^{\frac{1}{2}} / 2)}$$

It can be seen that if λ is known, the maximum deformation in the X direction can be calculated and predicted.

3. Numerical examples

3.1. Determination of the shear layer parameter λ

In this paper, by adjusting the coefficient of shear modulus to a thickness of the shear layer λ, the curing deformation of the component is consistent with the experimental results, then the parameters of the shear layer under specific process conditions are obtained. The example was taken from the literature [12], using prepreg T800HB/3900-2 as the laminate material which monolayer thickness is 0.16mm. The mould material is 6061-T6 aluminum and invar with each thickness of 10 mm. The mold parameters are shown in table 1, and the material parameters are shown in table 2.

Table 1. Properties of mold.

Mould material	t	α_T
Aluminum	10mm	23.1με/°C
Invar	10mm	2.9με/°C

Table 2. Properties of T800HB/3900-2.

Properties	E_1 /GPa	E_2, E_3 /Gpa	α_1/°C^{-1}	α_2,α_3/°C^{-1}	v_{12}, v_{13}	v_{23}	G_{12},G_{13} /GPa	G_{23} /GPa
Value	169	8.62	-0.001×10^{-6}	8.95×10^{-6}	0.355	0.41	5	1.22

According to [6], the component is laminate with four layers, which $L \times b = 254mm \times 25mm$, the material of the mold is 6061-T6 aluminum. Using the method described in this paper, the relationship between the maximum deformation of composite laminates and coefficient λ is shown in figure 2.

It can be seen from figure 2 that when the coefficient λ is about 0.19, the calculation are most consistent with the experimental results. The results of the comparison are shown in table 3:

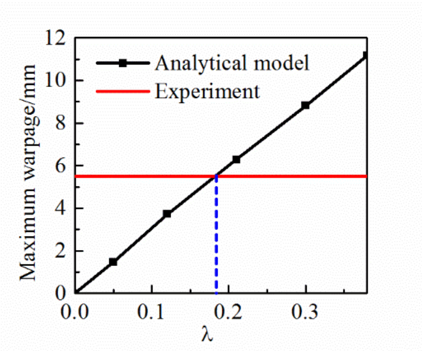

Figure 2. The relationship between the maximum deformation of the composite component and λ.

Table 3. Deformation comparison of T800HB/3900-2 composite.

Experiment	Analytical model	Error
5.498	5.60	1.8%

3.2. *Effects of characteristic parameters on coefficients* λ

Mezeix *et al.* [12] carried out curing deformation experiments on laminates of different length and thickness using molds made of steel. The effect of the interaction between the mold and the composites on the curing deformation was studied. The calculation model of this paper is used to calculate the curing deformation of laminates of different sizes. The results are shown in table 4 and the corresponding coefficients λ are shown in table 5.

Table 4. Comparison between experimental and calculated deformation of laminates of different thickness and length.

Ply	L(mm)	Experiment (mm)	Analytical model (mm)	Simulation (mm)	The analytical model error	The simulation model error
4	300	5.2	5.16	5.10	0.8%	2%
	400	9.19	9.17	8.0	0.2%	13%
	500	23.3	14.32	22.5	38.5%	5%
8	300	1.45	1.47	1.48	1.4%	2%
	400	2.37	2.6	2.96	9.7%	25%
	500	4.5	4.07	5.0	9.6%	11%
16	300	0.32	0.323	0.31	0.9%	3%
	400	0.6	0.57	0.71	5.0%	18%
	500	1.47	0.9	2.65	38.7%	80%

Table 5. λ of different plies

Ply	4	8	16
λ	0.72	0.68	0.55

From the calculation results in Table 4, it can be seen that the model in this paper can predict the curing deformation of the laminates well. At the same time, the coefficient λ hardly transforms with the change of the length, but with the change of the thickness of the laminates, the coefficient must be recalculated to predict the components of any length under the thickness. It can be seen from Table 5 that during the curing process of T800HB/3900-2 composites, the relationship between the coefficient λ and the number of layers can be obtained by the least squares method under the action of the Invar mold:

$$\lambda = -0.01446t + 0.785 \tag{12}$$

where t represents the number of laminates layers. The fitted curve between coefficient λ and laminate ply is shown in figure 3.

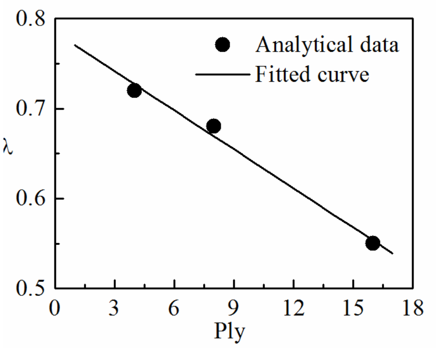

Figure 3. The fitted curve between coefficient λ and laminate ply.

3.3. *Verification of numerical calculation model and shear layer parameters*

To verify the accuracy of the numerical calculation model and the shear layer parameters λ, the experimental data in the literature [12] is used for validation. The component is a laminate with 6 layers, which size is $300mm \times 300mm$, the coefficient of that thickness can be calculated to be 0.698 by using the fitted curve. The calculations are shown in table 6:

Table 6. Verification of fitting accuracy of λ.

Analytical model	Experiment	Error
2.52	2.38	5.9%

It can be seen from table 6 that the coefficient obtained by the fitted curve can predict the maximum curing deformation of laminates accurately, thus proving the correctness of this fitting.

4. Conclusions

In this paper, a shear layer is introduced for the mold-component interaction during the curing process of the composites, that is, the interaction between the mold and the component is transmitted through the shear layer. The numerical model of curing deformation of composite laminates is established by introducing a shear layer parameter λ. The main conclusions are:

- ✓ It is proved by this model that the curing deformation is not directly related to the shear modulus and the thickness of the shear layer, but only to the ratio of the shear modulus to the thickness λ.
- ✓ Combining the experimental Several LED chip temperature-reducing methods have been proposed by researchers [6-10]. results with the calculation model, it can be concluded that λ hardly changes with the transformation of the length of the components, but varies with the ply of the laminates.
- ✓ The curing deformation obtained by using the calculation model of this paper is compared with the deformation measured by experiment. The results show that the model can predict the curing deformation of composite laminates with different length and thickness.

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