Simulation and Analysis on Residual Stresses for Unidirectional Thermoplastic Composites in Thermostamping Process

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1. Introduction

One constraint that limits the application of continuous fiber-reinforced polymer-matrix composites lies on the low production efficiency of traditional composite processes. However, the thermostamping process provides a fast and low-cost method in the mass production of high-quality advanced composite components, the cycle time of which can be in the range of 1 min.

Undesired process-induced distortions (PIDs) still remain a barrier for the further application of composites in engineering. In past decades, most studies on the PID subject were carried out for thermosetting composites manufactured by autoclave process, RTM etc. [1-3]. There is a consensus in the literature that both process features and material characteristics should be embedded in the PID calculation [4]. Different from autoclave process, RTM etc., the 2D blank in thermostamping is stamped into a 3D shape by external forces. Fiber reorientations always take place when doubly-curved structures are encountered. Moreover, stresses induced by the stamping of molds are preserved in components. A priori, fiber reorientations and stamping-induced stresses may influence PIDs for composites. However, up to now, there are few PID investigations for the thermostamping process with fiber reorientations and stamping-induced stresses considered. The objective of the present study is to analyze process-induced distortions for unidirectional thermoplastic composites in the thermoforming process and to evaluate the effects of fiber reorientations and stamping-induced stresses.

2. Experiments

The thermostamping setup is illustrated in Fig. 1. The uniaxial prepreg composed of a polypropylene (PP) matrix and E-glass fibers has been used. Before thermostamping, the prepreg was cut into squares and stacked into a blank, which was attached to the blank-holder frame by springs, as shown in Fig. 1(c). In thermostamping, the blank was first transferred into the radiant heater oven to be heated above its melt-temperature, then quickly transferred to the press for stamping. The press was equipped with male and female molds, and the mold temperature was kept at a target temperature of 70°C. Hemispheres with four different stacking sequences ($[0/90/0/90]_S$, $[0/90/0/0]_2$, $[0/90/0/90]_2$, [0/90/0/0]) were prepared

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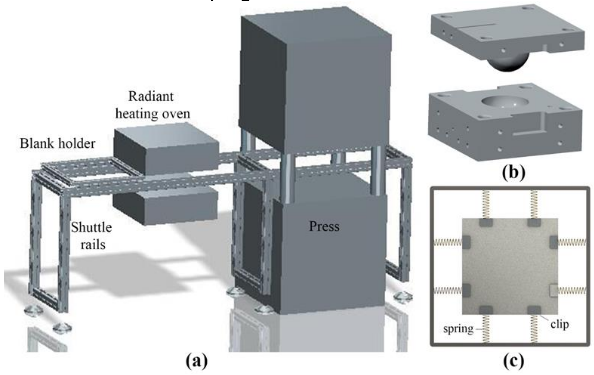

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3. Finite element simulations

The simulation process is divided into three parts: thermostamping, springback and trimming. The thermostamping process is considered as quasi-static. The die and punch are represented by analytical rigid bodies. Composite parts are discretized using S4R elements. An orthogonal constitutive model is developed to reflect fiber reorientations.

$$\mathbf{T}=\begin{bmatrix}\cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta\\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta\\ \sin\theta\cos\theta & -2\sin\theta\cos\theta & \cos^2\theta-\sin^2\theta\end{bmatrix} \quad (1)$$

$$\begin{Bmatrix}d\sigma_{11}\\ d\sigma_{22}\\ d\sigma_{12}\end{Bmatrix}=\mathbf{T}\begin{Bmatrix}Q_{11} & Q_{12} & 0\\ Q_{12} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{Bmatrix}\mathbf{T}^{\mathrm{T}}\begin{Bmatrix}d\varepsilon_{11}\\ d\varepsilon_{22}\\ d\varepsilon_{12}\end{Bmatrix}=\overline{\mathbf{Q}}\begin{Bmatrix}d\varepsilon_{11}\\ d\varepsilon_{22}\\ d\varepsilon_{12}\end{Bmatrix} \quad (2)$$

Where θ is the rotation angle of fibers, and Q is the effective stiffness matrix that reflects the stiffness change induced by fiber reorientations. A VUMAT subroutine is developed accordingly.

The deformed blank model is transferred from the thermostamping process to the springback procedure. A UEXPAN subroutine is implemented to reflect the effect of fiber reorientations on thermal expansion behaviours of composites. The trimming process is finally simulated by the “element birth and death" approach, to calculate the process-induced distortions and residual stresses of hemispheres in the end.

4. Results and discussion

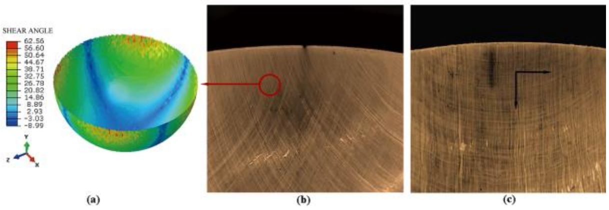

Fig.2 (a) simulation results of shear angles in the hemisphere; Experimental fiber orientations (b) in the 45° direction and (c) in the 0° direction ([0/90/0/90]s).

Simulation and experimental shear angle distributions in the hemisphere are displayed in Fig. 2. Shear angles are approximately equal to zero in the 0 ° and 90 ° directions. Shear angles reach their maximums in the directions of ±45 °. It is found that the predicted shear angle distributions show good correlation with experimental results.

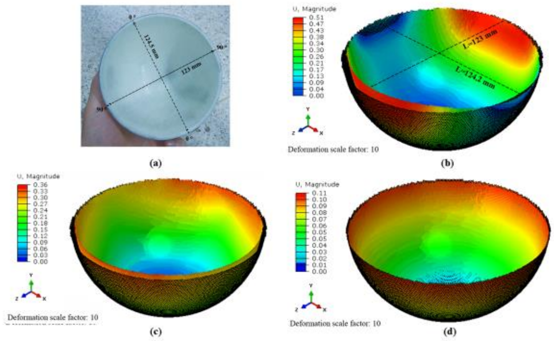

Fig.3 (a) Experimental profile of the [0/90/0/90]s hemisphere; (b) predicted PIDs of [0/90/0/90]s; (c) predicted PIDs neglecting stamping-induced stresses; (d) predicted PIDs neglecting stamping-induced stresses and fiber reorientations.

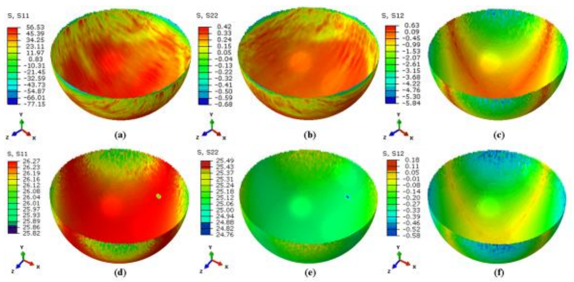

Fig.4 (a)-(c) stamping-induced stresses and (d)-(f) thermal stresses in the first ply of the [0/90/0/90]s hemisphere

It is shown in Fig. 3 (a)(b) that the simulation results of shape distortions agree well with experimental results. Therefore the proposed simulation method could accurately predict the residual stresses of hemispheres. It is found that regarding hemispheres with the symmetric lay-up [0/90/0/90]s, stamping-induced stresses play a dominant role in PIDs and determine the deformation trend as indicated in Fig. 3(c); fiber reorientations contribute approximately 76% to thermal distortions. Process induced distortions and residual stresses of asymmetrical lay-up hemispheres are investigated as well. It is found that stamping-induced stresses could be neglected in the PID prediction for the investigated three different asymmetrical lay-ups, and contributions made by fiber reorientations range from 18% to 28%.

5. Conclusion

A simulation method of residual stresses and process induced distortions (PIDs) is developed for unidirectional thermoplastic composites in the thermoforming process. A constitutive model is presented to reflect fiber reorientations in thermostamping. Additionally, stamping-induced stresses are embedded in the simulation. Good correlation is obtained between the prediction and experimental results. The effects of fiber orientations and stamping-induced stresses are analyzed for both symmetric and asymmetric lay-up hemispheres. It is found that stamping-induced stresses play a dominant role in PIDs for the symmetric lay-up ([0/90/0/90]S) hemisphere and determine the deformation trend; stamping-induced stresses could be neglected in the PID prediction for three asymmetrical lay-up hemispheres. Fiber orientations have a distinct effect on the magnitude of PIDs. Contributions made by fiber reorientations to thermal distortions range from 18% to 28% for three asymmetric lay-up hemispheres, and more than 76% for the symmetric lay-up ([0/90/0/90]S) hemisphere.

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