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A lamination model for forming simulation of woven fabric reinforced thermoplastic prepregs

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ABSTRACT

In order to characterize the large deformation, anisotropy and multi-field coupling behaviors of woven fabric reinforced thermoplastics (WFRTP) in forming, a lamination model combining thermoplastic resin and woven fabric reinforcements is established. The WFRTP is modeled as a laminated structure with impregnated woven fabric layers sandwiched between two thermoplastic resin layers. The thermo-mechanical coupling and viscosity resulted from melted resin matrix is characterized by an isotropic visco-hyperelastic model, while the impregnated woven fabric reinforcement is defined by an anisotropic hyperelastic model. The proposed lamination model is demonstrated on forming simulation of a WFRTP over a double-curvature mold. The effects of processing parameters including forming temperature and blank holder force on wrinkling are investigated. The proposed model is simple and easy for material parameter determination. It provides a theoretical foundation for numerical simulation and processing optimization of WFRTP forming.

1. Introduction

In the past several decades, researches of woven fabric composites mainly focus on thermoset matrix. But for automobile industry, high productivity and recycling are the basic requirements [1]. Thus many research resources have been put into improving thermoset resin methods to raise production efficiency, such as by introducing fast curing resin system [2] or by using high pressure resin transfer molding technology [3]. However, these improvements have not solved the application problems existed in automobile industry [4]. Compared to woven fabric reinforced thermoset composites, woven fabric reinforced thermoplastic composites (WFRTP) have the advantages of being recyclable, high forming efficiency, high impact toughness and a long shelf life [5,6], which make them have a wide range of application potential in automobile industry.

Due to the fact that the viscous and curing characteristics of thermoplastic resins are significantly different from those of thermoset resins [7], it is necessary to develop an appropriate forming process for WFRTP composites which fits the forming characteristics of thermoplastics and meanwhile matches the demand of mass production in automotive industry. Thermo-stamping is such a process that aims at WFRTP and imitates sheet metal forming [8]. Half melt and solid-state stamping is a viable option for producing simple parts from semi-crystalline thermoplastic matrix composite sheet. Scholars had carried out various researches on the stamp forming of textile thermoplastic composites. The effects of layup sequence, ply thickness and bend radius on the parts' quality and mechanical performance were evaluated during thermoforming of S-shape parts made of carbon fiber/polyphenylene sulfide thermoplastic composites [9]. Hou et al. [10,11] studied both UD and woven glass fiber/polypropylene (GF/PP) composites and found that forming pressure highly affects the thickness distribution of UD fiber parts, while has little influence on that of woven fabric parts. De Luca et al. [12] found from forming experiments that compared to UD composites, woven composites are more liable to fiber rupture but have better resistance to wrinkling. The influence of processing parameters such as pressure, temperature, loading rate and holding time were experimentally evaluated by Boucher et al. [13].

However, to achieve thermo-stamping of WFRTP with high efficiency and low cost, the need to reduce the time and cost of repeated trial and error in process parameters adjustment and mold design optimization lies ahead. Therefore, accurate and effective numerical simulation for the forming process is necessary. Thermo-stamping process of WFRTP involves large deformation, anisotropy and thermo-mechanical coupling phenomenon, which bring great difficulties to accurate numerical simulation. With the maturity of finite element method, a growing number of scholars carried out numerical simulations for composite forming process to make cost effective parts from WFRTP. Harrison et al. [14] simulated WFRTP forming over a double

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dome geometry mold based on a non-orthogonal constitutive model [15]. O'Bradaigh and Pipes [16,17] implemented composite sheet-forming simulation by treating composite laminates as a transversely isotropic Newtonian fluid with fibers of inextensibility. De Luca et al. [12] studied thermo-forming of fiber-reinforced composites by using shell elements for each ply which was assumed as a thermo-viscous matrix with elastic fiber reinforcements. Wang et al. [18] developed a numerical approach for thermo-forming of multilayer thermoplastic prepregs in which each ply was modeled by semi-discrete shell elements with tension, in-plane shear and bending stiffness. Guzman-Maldonado et al. [19,20] simulated thermoplastic prepreg composites forming with a finite strain viscoelastic constitutive model [21] based on convolution integrals [22,23]. As an extension of [24], a simple hyperelastic model was proposed to characterize the large deformation behavior of WFRTP prepregs by considering the damping effect of resin matrix [25].

This paper aims to propose an approach for simulating thermo-forming process of WFRTPs with a lamination model, which is relatively simple but still effectively capture the essential material behaviors of WFRTPs in forming. The WFRTP is modeled as a laminated structure with impregnated woven fabric layers sandwiched between two thermoplastic resin layers. The viscosity effect associated with temperature of melted thermoplastic matrix is characterized by an isotropic visco-hyperelastic model. The impregnated woven fabric reinforcement is defined by a previously developed anisotropic hyperelastic model [25]. The remains of the paper are organized as follow. Section 2 gives a detailed description of the lamination model. Then the model is exemplified on a T300-3K 5-harness satin woven carbon fabric/PPS prepregs in Section 3. Procedure for material parameter determination and model validation are also provided in this section. Application of the proposed model on forming simulation is demonstrated in Section 4. Section 5 gives the conclusions.

2. Lamination model for woven fabric reinforced thermoplastic prepregs

Under thermoforming, thermoplastic prepregs can be modeled as a laminated structure composing *A*: *B*: *A* (thermoplastic matrix: impregnated fabric reinforcements: thermoplastic matrix), in which *A* and *B* are perfectly bonded to each other and no separation between *A* and *B* is considered. The matrix is assumed to be isotropic and visco-hyperelastic with compressibility [26]. The impregnated woven fabric is characterized with an anisotropic hyperelastic model [25].

2.1. Constitutive model for melting matrix

During thermo-stamping, thermoplastic resin is at a high elastic state or viscous state for the temperature is close to or higher than the melting point of the resin in order to render the woven fabric thermoplastic prepreg deformation easily. However, viscosity of thermoplastic matrix originates from the microstructure of the material and depends on its chemical constitution, which is not the main consideration at this paper. A phenomenological temperature-dependent visco-hyperelastic model is thus proposed for thermoplastic to describe its viscous elastic state at the melting temperature.

In continuum mechanics, $\mathbf{F}(\mathbf{x},t) = \partial\mathbf{x}/\partial\mathbf{X}$ is the deformation gradient tensor and $\mathbf{C}(\mathbf{x},t)$ is the right Cauchy-Green deformation tensor defined as

$$\mathbf{C}(\mathbf{x},t) = \mathbf{F}^T\cdot\mathbf{F} \tag{1}$$

where $\mathbf{X}$ represents the position of a material particle in the reference configuration, while $\mathbf{x}$ is the position of the corresponding particle in the current configuration.

The deformation rate is defined as

$$\dot{\mathbf{C}}(\mathbf{x},t) = \frac{\partial\mathbf{C}}{\partial t} = \dot{\mathbf{F}}^T\cdot\mathbf{F} + \mathbf{F}^T\cdot\dot{\mathbf{F}} \tag{2}$$

The strain invariants of $\mathbf{C}(\mathbf{x},t)$ are

$$I_1 = \mathbf{I}:\mathbf{C} = tr(\mathbf{C}),\ I_2 = \frac{1}{2}[I_1^2-(\mathbf{I}:\mathbf{C}^2)] = \frac{1}{2}[(tr\mathbf{C})^2-tr(\mathbf{C})^2],\ I_3 = \det(\mathbf{C}) \tag{3}$$

where $\mathbf{I}$ is the second order identity tensor.

The strain rate invariants are given as follows

$$J_1 = \mathbf{I}:\dot{\mathbf{C}} = tr(\dot{\mathbf{C}}),\ J_2 = \frac{1}{2}(\mathbf{I}:\dot{\mathbf{C}}^2) = \frac{1}{2}tr(\dot{\mathbf{C}}^2),\ J_3 = \det(\dot{\mathbf{C}})J_4 = \mathbf{I}:(\mathbf{C}\cdot\dot{\mathbf{C}}) = tr(\mathbf{C}\cdot\dot{\mathbf{C}}),\ J_5 = \mathbf{I}:(\mathbf{C}\cdot\dot{\mathbf{C}}^2) = tr(\mathbf{C}\cdot\dot{\mathbf{C}}^2) \tag{4}$$

A Helmoltz free energy function W is defined to characterize the mechanical behavior of melting matrix under large deformation. Considering the strain rate dependent characteristic of thermoplastic resin, the energy function can be decomposed into a hyperelastic part W^e and a viscous potential part ψ^v. The hyperelastic energy part W^e is proposed as a function of material point position $\mathbf{x}$, the right Cauchy-Green tensor $\mathbf{C}$ and temperature T with a neo-Hookean form,

$$W^e = W^e(\mathbf{x},\mathbf{C},T) = W^e(I_i,T) = C_{10}(T)(\bar{I}_1-3) + \frac{1}{D_1(T)}(J-1)^2 \tag{5}$$

where $J = \det(\mathbf{F}) = \sqrt{I_3}$ is the volume ratio, and C_{10}, D_1 are material parameters related to temperature with units of MPa and MPa^{-1}, respectively. T is the forming temperature. $\bar{I}_1$ is the first deviatoric invariant, $\bar{I}_1 = J^{-\frac{2}{3}}I_1$.

A macro-phenomenological model is proposed to characterize the viscous response from the resin by a strain rate dependent viscous strain energy function

$$\psi^v = \psi^v(\mathbf{x},\mathbf{C},\dot{\mathbf{C}},T) = \psi^v(J_i,T) = \eta_1(T)J_2(I_1-3) \tag{6}$$

where $\eta_1(T)$ is a viscous material parameter with units of MPa·s.

The second Piola-Kirchhoff stress tensor is calculated by

$$\mathbf{S} = \mathbf{S}^e + \mathbf{S}^v = 2\left[\frac{\partial W^e}{\partial\mathbf{C}} + \frac{\partial\psi^v}{\partial\dot{\mathbf{C}}}\right] = 2\left[\sum_{i=1}^{3}\left(\frac{\partial W^e}{\partial I_i}\frac{\partial I_i}{\partial\mathbf{C}}\right) + \sum_{i=1}^{5}\left(\frac{\partial\psi^v}{\partial J_i}\frac{\partial J_i}{\partial\dot{\mathbf{C}}}\right)\right] \tag{7}$$

With the hyperelastic and viscous energy parts defined, the second Piola-Kirchhoff stress tensor can be obtained by substituting Eqs. (5) and (6) into (7)

$$\mathbf{S}^e = 2\frac{\partial W^e}{\partial\mathbf{C}} = 2C_{10}I_3^{-\frac{1}{3}}\left(\mathbf{I}-\frac{1}{3}I_1\mathbf{C}^{-1}\right) + \frac{2}{D_1}\left(I_3-I_3^{\frac{1}{2}}\right)\mathbf{C}^{-1} \tag{8}$$

$$\mathbf{S}^v = 2\frac{\partial\psi^v}{\partial\dot{\mathbf{C}}} = 2[\eta_1(I_1-3)\dot{\mathbf{C}}] \tag{9}$$

2.2. Constitutive model for impregnated woven fabric reinforcements

On the basis of previous work [25], an anisotropic hyperelastic constitutive model with fiber-fiber-matrix interaction is adopted in the lamination model to characterize the impregnated woven fabric reinforcements. The strain energy per unit volume W can be expressed as a scalar tensor function of the original fiber directional unit vectors for weft yarns $\boldsymbol{a}_0$ and warp yarns $\mathbf{b}_0$ and the right Cauchy-Green strain tensor $\mathbf{C}$, i.e., $W = W(\mathbf{C},\mathbf{a}_0,\mathbf{b}_0)$. On the other hand, the strain energy W can be written as a scalar function of a set of principal invariants [25] namely

$$W(\mathbf{C},\mathbf{a}_0,\mathbf{b}_0) = W(I_1,I_2,I_3,I_4,I_5,I_6,I_7,I_8,I_9) \tag{10}$$

$$I_4 = \mathbf{a}_0\cdot\mathbf{C}\cdot\mathbf{a}_0 = (\lambda_F^a)^2,\ I_6 = \mathbf{b}_0\cdot\mathbf{C}\cdot\mathbf{b}_0 = (\lambda_F^b)^2,\ I_5 = \mathbf{a}_0\cdot\mathbf{C}^2\cdot\mathbf{a}_0,\ I_7 = \mathbf{b}_0\cdot\mathbf{C}^2\cdot\mathbf{b}_0,\ I_8 = \mathbf{a}_0\cdot\mathbf{C}\cdot\mathbf{b}_0,\ I_9 = \mathbf{a}_0\cdot\mathbf{C}^2\cdot\mathbf{b}_0 \tag{11}$$

During thermoforming of woven fabric prepregs, the main deformation modes are extension along the fiber yarn directions, intra-ply shear deformation within matrix and bending deformation [20]. Generally, the bending stiffness of the fiber is so small that it can be