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Mini Review

Numerical Simulation of Curing-Induced Deformation and Residual Stress in Thermosetting Resin-Based Composites

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Abstract: Curing-induced deformation and residual stress pose threats to the application of composites. Accurate prediction of curing deformation and residual stress can provide adjustments for the structural and process design of composites, reducing curing deformation and residual stress. Numerical simulation methods are widely used due to their simplicity and high predictive accuracy. This paper primarily introduces the numerical simulation process for composite curing deformation and residual stress, which includes the heat conduction-curing module, the flow and compaction module, and the stress-deformation module. It focuses on the latest developments in the constitutive equations within the stress-deformation module and the interactions between models and components, providing directions and references for predicting curing deformation and residual stress. The paper briefly discusses the main development directions in the prediction of curing deformation and residual stress in composites.

Keywords: Residual Stress, Curing Deformation, Numerical Simulation, Constitutive Relations, Compaction, Mold-Component Interaction Force

INTRODUCTION

The introduction is a beginning section of a manuscript which states the purpose of the study, overviews or summarizes previous findings and progress related to this study, and indicates its significance in this research field. It is generally followed by the body and discussion.

Advanced thermosetting resin-based composites are characterized by their lightweight, high specific strength/modulus, excellent fatigue resistance, and strong corrosion resistance, making them widely used in aerospace, marine, and other fields. Unlike traditional composites, where the material is processed into components, thermosetting resin-based composites are formed as both the material and the component simultaneously. This characteristic allows for the use of integrated molding techniques, significantly reducing the number of parts and connections, enhancing structural reliability, and lowering production costs[1-2].

During the molding process, heating is generally employed to increase the ambient temperature around the composite material, triggering resin curing. Throughout the molding process, the resin undergoes a series of physical and chemical changes, leading to substantial alterations in the material state. After demolding, composites often experience curing deformation and residual stress. Excessive residual stress can lead to delamination between layers and resin rupture, adversely affecting the performance of the composite. Similarly, significant curing deformation can challenge the assembly of composite components, potentially exceeding assembly tolerances and leading to assembly failure or component rejection. Curing deformation is a critical factor impacting the quality of integrated molded composite components and is one of the key issues in composite design and manufacturing.

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To mitigate curing deformation and residual stress, traditional methods involve iterative adjustments and compensatory design of the curing process curve and mold design based on experience and process trials[3-4]. However, these methods may be ineffective for complex shapes or new composite materials, and experimental approaches can be inefficient. Accurate prediction of curing deformation and residual stress can significantly improve mold design efficiency and reduce costs. Numerical simulation methods are currently the most common and effective approach. This paper reviews the progress in numerical simulation methods for curing deformation and residual stress in thermosetting resin-based composites, focusing on advancements in constitutive models and interaction force characterization between mold and component. Additionally, it briefly discusses the main development directions for predicting curing deformation and residual stress in composites.

Composite molding processes

Composite molding processes are numerous, each with its advantages, disadvantages, and suitable applications. Advanced thermosetting resin-based composite molding technologies often utilize autoclave molding, resin transfer molding, and vacuum-assisted infusion molding. During a typical curing process, the composite undergoes five main stages (see Figure 1):

Flow Stage: Also known as the pre-gelation stage. In this stage, the resin has low viscosity and is in a liquid (viscoelastic) state. Under operational pressure, air between the prepreg layers is expelled, and the preform is compacted. If a peel ply is used (applied after laying down the prepreg), it absorbs excess resin. As the temperature rises, the resin's viscosity increases, making flow difficult. At the gelation point, the resin ceases to flow, defining the composite's thickness and fiber volume fraction (Vi)[5]. During this stage, the resin undergoes curing shrinkage and thermal expansion. However, as the resin is still liquid, the transfer of forces between the resin and fibers is weak, so these changes have minimal impact on curing deformation and residual stress. Nevertheless, some studies indicate significant interaction forces between the mold and the fiber bed[6-9].

Gelation and Glass Transition Stage: In this stage, the process temperature is set above the resin's glass transition temperature (Ta) (see Figure 1), placing the composite in the rubbery state. As temperature increases, the curing rate accelerates, and the curing degree rises. The molecular weight of the resin system increases, and branching increases. Despite the resin exhibiting strong viscoelasticity at high temperatures, the relaxation time is minimal, and the modulus rapidly stabilizes to the equilibrium modulus (rubbery modulus). The curing reaction is most intense near the vitrification point, with the resin showing pronounced viscoelasticity. Curing shrinkage mainly occurs during this stage [10]. Due to the decreased modulus, curing shrinkage strain and thermal expansion in this stage do not produce significant residual stress but do affect curing deformation[11].

Post-Glass Transition Holding Stage: At the glass transition point, the process temperature equals the resin's glass transition temperature (Ta). As curing continues, the glass transition temperature (Tg) becomes higher than the set process temperature, and the composite exhibits glassy properties. Since curing degree increases minimally during this stage, the resulting shrinkage strain is small, having minimal impact on residual stress[8,12].

Cooling Stage: During cooling, the material remains in a glassy state, and curing reactions end before cooling starts. The mismatch in thermal expansion coefficients between the mold and the component, or between layers, significantly contributes to curing deformation and residual stress[8,12]. Early studies on composite curing deformation and residual stress primarily focused on the contribution of physical and chemical phenomena during the cooling stage[13-14].

Post-Demolding Stage: After demolding, subsequent processes such as cutting or trimming can affect the residual stress and deformation of the component.

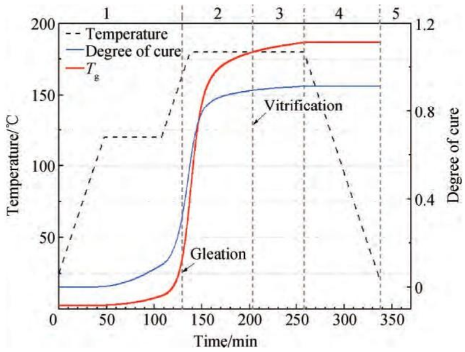

Figure 1: Typical curing process curve showing the variation of curing degree and material behavior with temperature and time.

Numerical Simulation Process

Numerical simulation is the most widely used method for predicting curing deformation and residual stress in composite components[15-26]. During curing, composites transition through three material states: viscous, rubbery, and glassy. The focus of numerical simulation is to accurately represent the series of physical and chemical processes occurring during these phases.

Figure 2 illustrates the workflow for predicting curing deformation and residual stress in composites. The numerical model for this prediction includes three modules: the thermal conduction-curing module, the flow and compaction module, and the stress-deformation module. The thermal conduction-curing module analyzes the distribution and variation of temperature and curing degree within the composite. The flow and compaction module calculates the changes in fiber volume fraction (Vf) and the thickness distribution of laminated panels. The stress-deformation module computes the stress-strain distribution and displacement within the composite. Throughout the curing process, these three modules are interrelated and occur simultaneously.

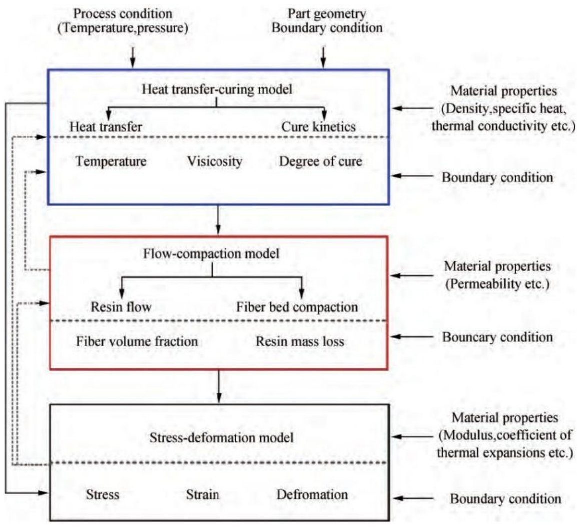

Figure 2: Workflow for Predicting Curing Deformation in Composites Using Numerical Methods

Currently, the most commonly used software for numerical simulation of curing deformation and residual stress includes ANSYS, ABAQUS, and COMSOL. These tools can consider two or three of the modules shown in Figure 2 simultaneously. However, coupling all three modules involves substantial computational effort and requires numerous material parameters, making it less common.

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The prevailing approach is sequential coupling, where the composite's behavior during curing is analyzed in stages. First, a thermal conduction-curing analysis is performed, and the resulting temperature and curing degree within each increment are input into the flow and compaction analysis. This analysis calculates the parameters needed for the flow and compaction model based on temperature and curing degree. Subsequently, the flow and compaction analysis yields the distribution of variables such as fiber volume fraction (Vf) within each increment. The results from these two analyses are then used as inputs for the stress-deformation model, which calculates the parameters required for the mechanical model related to the imported variables, thus determining the stress and displacement in the composite.

Sequential coupling does not account for the feedback effects of stress-deformation results on the flow and compaction and thermal conduction-curing stages (i.e., the dashed lines in Figure 2 are not considered). Most research currently focuses on either a single module or the coupling of two modules. For example, Zhang et al.[27], Yan et al.[28-29], and Shin et al.[30] coupled thermal conduction-curing with flow and compaction models to analyze changes in composite thickness and fiber volume fraction during curing. In contrast, Ma et al.[31], Tan et al.[32], Nar et al.[33], and Li et al.[34] used sequential coupling methods to predict curing deformation and residual stress, omitting the flow and compaction model. The following sections will detail these three modules, with a particular focus on the stress-deformation module.

Conclusion and Outlook

As the use of resin-based composites increases in fields such as aerospace and maritime industries, and as application requirements continue to evolve, achieving integrated manufacturing has become a crucial method for enhancing structural reliability and reducing manufacturing costs. However, integrated manufacturing also presents challenges in composite design and process control, requiring more precise management of curing deformation and residual stress. Future work can focus on the following areas:

1) Pre-Gelation Mold-Component Interaction: Current predictions of residual stress and curing deformation often overlook the impact of mold-component interactions before gelation. Research has shown that significant interactions between the mold and fiber bed exist prior to gelation, which can affect curing deformation and residual stress. To improve the accuracy of numerical simulations, it is necessary to quantify these interactions.

2) Curing Deformation and Residual Stress in Large Thickness and High Curvature Components: While extensive research has been conducted on curing shrinkage and thermal expansion in small and thin components, large-thickness and high-curvature composites present unique challenges. In these cases, resin flow and uneven fiber distribution, especially at corners, lead to significant temperature and curing degree gradients in the thickness direction. There is a need for more research on how these factors affect curing deformation and residual stress in such components.

3) Impact of Residual Stress on Composite Performance: Residual stress can lead to micro-cracking at the matrix and interface, creating internal defects that affect the propagation of matrix cracks, interface debonding, and inter-layer delamination. These issues can significantly impact the overall performance and lifespan of the composite, particularly its fatigue resistance. Future research should focus on quantifying the effects of residual stress on composite performance.

DECLARATIONS

Authors' contributions

All authors contributed equally.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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