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Research on process parameters of composite components based on Simulation

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Abstract

This study systematically investigates the effects of process parameters (mold temperature, curing pressure, resin flow rate, curing time) on composite molding quality via simulation analysis, orthogonal experiments, and simulation-driven genetic algorithm optimization. Physical mechanism modeling reveals key processes (resin flow, curing reaction, fiber impregnation), supporting defect prediction and parameter optimization. Orthogonal experiments clarify parameter interactions, while optimization using genetic algorithms significantly enhances molding quality (reducing defects, improving curing uniformity and mechanical properties), validated by experiments. Results confirm these parameters are critical for quality, with the proposed method improving production efficiency and product reliability. Future work will extend to other composites, refine multi-physics coupling models, and develop smarter algorithms to advance industrial applications.

Keywords

Composite Materials; Process Parameter Optimization; Molding Process; Orthogonal Experimental Design; Genetic Algorithm; Molding Quality

1. Introduction

Driven by growing demands for lightweight and high-strength materials in high-end equipment such as aerospace, automotive manufacturing, and wind power, composite materials have become critical structural materials due to their excellent mechanical properties and design flexibility. However, composite molding involves complex multi-physical field coupling processes (e.g., resin flow, fiber impregnation, heat conduction, and curing), where improper control can easily induce defects (e.g., voids, dry spots, porosity), compromising component performance and service life. Thus, investigating molding physical mechanisms, developing accurate simulation models, and optimizing parameters to improve molding quality hold significant theoretical and engineering value. Existing studies on composite molding simulation have made progress globally: foreign research early adopted numerical simulations (e.g., ANSYS Polyflow, Moldflow, COMSOL) for resin flow and curing, enhancing predictability; domestic research, though starting later, has advanced in modeling, defect prediction, and process optimization. Yet challenges remain, including insufficient modeling accuracy, difficulty in parameter acquisition, and large simulation-experiment discrepancies, necessitating further study. This paper focuses on typical composite molding processes, systematically investigating physical modeling, simulation analysis, and parameter optimization.

2. Theoretical Basis of Composite Molding and Analysis of Process Influencing Factors

2.1. Characteristics of Molding for Composite Components

Composites consist of a reinforcement phase (e.g., fibers) and a matrix phase (e.g., resin), with their properties strongly dependent on fiber alignment, resin impregnation, and curing behavior during molding. Compared to traditional metallic materials, composite molding exhibits strong anisotropy, significant interfacial effects, and complex material behavior, posing significant challenges to achieving precise molding and quality control. Additionally, thermal expansion mismatch between fibers and resin induces internal stresses and deformations.

Composite components are often manufactured via layered processes, requiring not only full resin impregnation and curing but also consistent and stable fiber alignment during molding. The process is influenced by multiple parameters (e.g., temperature, pressure, flow rate). To meet structural performance and weight requirements, higher precision in process control is demanded, driving the advancement of molding simulation and parameter optimization technologies.

2.2. Overview of Commonly Used Composite Molding Processes

There is a wide variety of composite molding processes, with different techniques suited to distinct component types and application scenarios. Common processes include Resin Transfer Molding (RTM), Vacuum-Assisted Resin Infusion (VARTM), Autoclave Molding, Automated Fiber Placement/Automated Tape Laying (AFP/ATL), and Compression Molding, among others. These processes differ significantly in terms of equipment requirements, molding cycle times, and product quality, necessitating rational selection based on component structure and application needs.The table below provides a comparison of common composite molding processes.

Table 1. Comparison of Commonly Used Composite Molding Processes

Forming Process	Process Characteristics	Scope of Application
RTM	Resin is injected into the mold cavity under pressure, infiltrating the dry fiber preform	Small and medium-sized complex components,mass production
VARTM	Utilizing vacuum to drive resin flow, the process equipment is simple	Large structural components, such as wind turbine blades and ship hull

		parts
Autoclave molding	Composite materials are cured and molded through high temperature and high pressure	High-performance aerospace components

Additionally, composite molding is prone to various defects, often arising from the combined effects of material properties and improper process control. Common defects include voids, dry spots, resin-rich areas, fiber wrinkling, and high porosity. Such defects not only degrade mechanical properties but also potentially induce failures during long-term service, underscoring the critical importance of molding quality control. Table 2 summarizes common molding defects and their causes.

Table 2. Common Molding Defects and Their Causes

Defect Type	Possible causes	Affect the result
Bubble/Pore	Excessively fast injection speed, high resin viscosity, and poor exhaust	Reduced interfacial bonding force and decreased strength
dry spot	The flow front resin is not fully infiltrated, and the preform has poor permeability	Local structural failure, stress concentration
Fiber wrinkling	Uneven molding pressure and inaccurate positioning of fiber preform	Severe decrease in local strength

2.3. The mechanism of how main process parameters affect molding quality

The molding process parameters are key factors determining the molding quality, mainly including pressure, mold temperature, resin flow rate, curing time, etc. These parameters are coupled and directly affect the flow behavior, wetting efficiency, and curing degree of the resin. For example, resin viscosity fluctuates significantly with temperature changes. An excessively high flow rate may cause fiber disturbance, while an excessively low flow rate affects mold filling efficiency; and temperature is closely related to the curing rate, which must be precisely controlled.

To systematically analyze the mechanism of action of each parameter, a corresponding physical model can be constructed for analysis through simulation methods. The following table summarizes the main parameters and their influencing methods.

Table 3. Main parameters and their influencing ways

process parameters	Control function	Explanation of the impact mechanism
mold temperature	Control resin viscosity and curing rate	An increase in temperature reduces viscosity, but excessive heat can lead to premature solidification
pressure	Drive resin flow	Insufficient pressure can lead to incomplete curing, while excessive pressure may cause deformation of the component
Resin viscosity	Determine mobility	Excessive viscosity makes it difficult to penetrate the prefabricated body, affecting the quality of infiltration

3. Simulation modeling and model validation of molding process

3.1. Modeling of Physical Mechanism in Forming Process

The molding process of composites primarily involves physical phenomena such as resin flow, curing, heat transfer, and fiber impregnation. Resin flow, governed by its rheological properties, typically exhibits non-Newtonian behavior, with flow characteristics dependent on temperature and shear rate. Curing, a chemical transition from liquid to solid resin, proceeds at a rate influenced by temperature and reactant concentration. Adequate fiber impregnation—critical to forming a robust matrix-fiber interface and ensuring composite mechanical performance—requires thorough resin penetration into fibers during molding. However, factors including complex mold geometry, fiber anisotropy, and resin viscosity often lead to defects such as incomplete curing, void entrapment, and dry spots, significantly degrading the final composite quality.

Thus, establishing accurate physical mechanism models is critical for predicting molding defects and optimizing process parameters. Key components include fluid dynamics, heat transfer, and curing reaction kinetics models. Fluid dynamics models typically use the Navier-Stokes equations to govern resin flow; heat transfer models apply Fourier's law to predict temperature field distribution; and curing reaction kinetics models characterize resin curing rates via mathematical frameworks such as the Kamal model. Through the coupling of these models, resin flow, heat transfer, and curing processes can be accurately simulated, enabling the prediction of quality variations during composite molding. Simulation results provide robust support for optimizing process parameters, reducing defects, and enhancing material performance.

3.2. Simulation Platform and Model Establishment Method

To enable efficient simulation of composite molding processes, selecting an appropriate simulation platform is critical. Commonly used platforms, such as ANSYS, COMSOL, and Moldflow, handle multi-physics coupling and support integrated analysis of fluid, thermal, and curing processes. For instance, ANSYS excels in fluid dynamics and thermal conduction simulation, leveraging the Navier-Stokes equations to model resin flow and integrating heat transfer equations with curing reaction models to simulate temperature distribution and curing progression during composite molding. COMSOL, in turn, offers more flexible multi-physics coupling capabilities, particularly suitable for scenarios requiring complex coupled analysis of flow, temperature, and curing.

When developing a simulation model, the first step involves accurately constructing the geometric model and discretizing it into a mesh. Mesh refinement critically impacts simulation accuracy, especially in key regions such as resin flow and curing, where finer meshes are necessary to capture flow and curing details. Next, boundary conditions and material parameters are defined based on actual process conditions, including resin viscosity, curing temperature, and fiber distribution. The fluid domain typically employs a non-Newtonian fluid model, while the thermal conduction domain accounts for the multi-layered structure of composites and heat exchange between layers. Finally, an appropriate solver is selected to perform the simulation, followed by result analysis, molding quality evaluation, and process optimization. This approach enables efficient prediction of physical changes during composite molding, facilitating process parameter optimization and defect reduction.

Figure 1. Modeling diagram of air domain in hot press tank

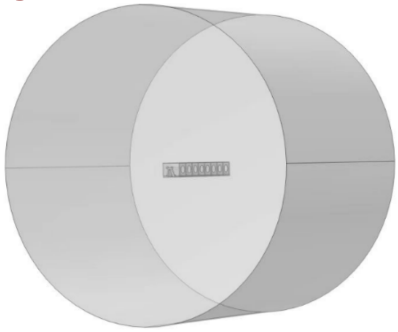
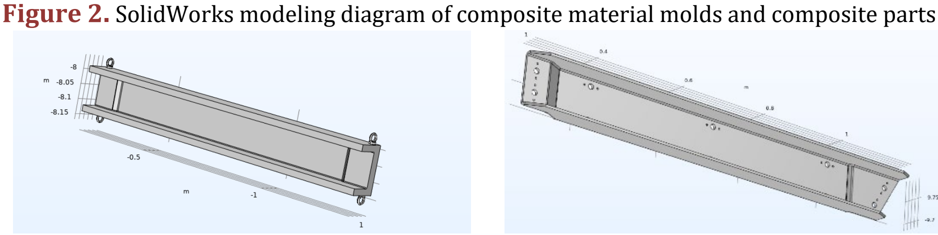


Figure 2. SolidWorks modeling diagram of composite material molds and composite parts



3.3. Material parameters and boundary condition settings

The selection of material parameters is critical for accurately predicting composite molding processes. In this study, epoxy resin (matrix) and glass fiber (reinforcement) were chosen as composite constituents: epoxy resin, a widely used matrix material, exhibits high hardness and favorable thermal stability (density: 1.15 g/cm^3; viscosity: 350 Pa·s at 20°C), making it suitable for processes like Resin Transfer Molding (RTM); glass fiber, the reinforcement, features high specific strength and modulus (density: 2.5 g/cm^3; modulus: 70 GPa), effectively enhancing composite rigidity. Fiber Volume Fraction (FVF), a key parameter governing overall composite performance, was set to 40% in this work (i.e., 40% of the composite volume is occupied by glass fibers), balancing high strength with controlled weight. Optimizing material parameter matching significantly improves resin-fiber interfacial bonding quality, thereby enhancing the mechanical performance and reliability of components.

Table 4. material parameter details

material	physical properties	numerical value	unit
Epoxy resin (EP)	density	1.15	g/cm^3
	viscosity (20 ° C)	350	Pa·s
	Specific heat capacity	1.4	J/g·K
	Thermal conductivity	0.25	W/m·K
	Elastic modulus	3.8	GPa
	curing temperature	150	°C

fiberglass	density	2.5	g/cm^3
	Elastic modulus	70	GPa
	tensile strength	1.5	GPa
	Fiber direction laying	± 45 ° staggered laying	

Boundary condition settings directly determine the accuracy of composite molding simulation models. In this study, temperature, pressure, and flow rate boundary conditions were configured to replicate real-world molding processes: the mold temperature was set to 150°C to ensure sufficient epoxy resin curing and maintain the strength and hardness of molded parts; the pressure was set to 0.6 MPa to guarantee adequate resin impregnation of fibers, preventing defects such as voids or dry spots. Additionally, resin flow rate and curing time (set to 60 minutes)—both critical to molding quality—were selected to ensure complete resin curing and optimal mechanical performance.

Mesh discretization accuracy directly influences the accuracy and reliability of composite molding simulation results. To ensure precise simulation of resin flow and curing processes, a refined mesh generation method was employed, with a focus on key regions such as resin flow zones and fiber preform areas: the resin flow region was discretized with a 2 mm mesh size to fully capture fluid dynamics; the fiber region adopted a 1 mm mesh to precisely model fiber distribution effects, enhancing the simulation of resin impregnation and fiber arrangement; the mold surface was also meshed at 1 mm to ensure accurate transfer of temperature and degree of cure. This refined meshing strategy enables the simulation model to more realistically reflect physical phenomena during molding, particularly improving the precision of local heat transfer, resin flow, and curing simulations in mold filling and curing stages, thereby enhancing the alignment between simulation results and actual molding processes as well as predictive accuracy.

4. Simulation driven orthogonal test

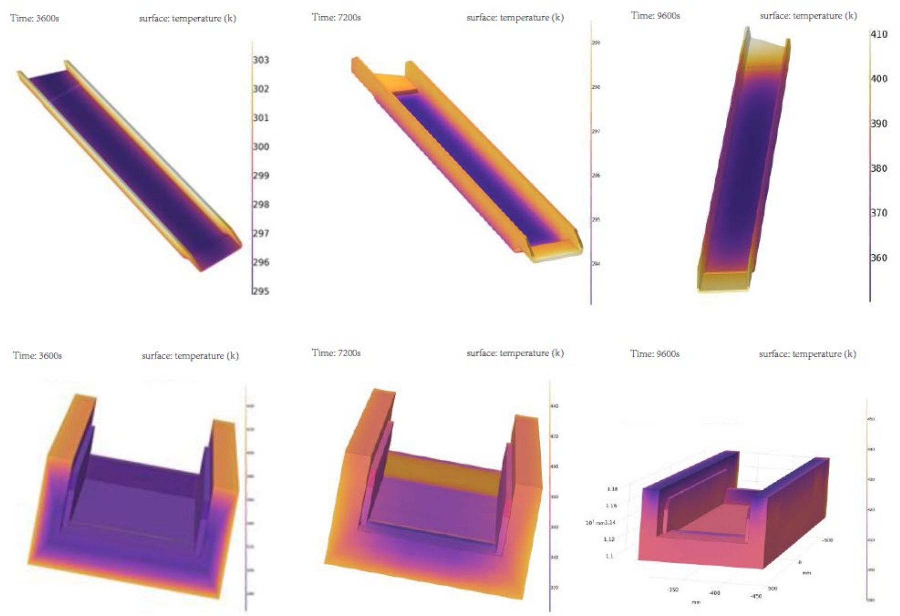
Orthogonal experimental design is an efficient methodology widely used in process optimization and parameter tuning. For composite molding processes, key influencing factors on molding quality include mold temperature, curing pressure, resin flow rate, and curing time. This study employs orthogonal experimental design to scientifically evaluate the effects of these factors on molding quality and identify optimal process parameter combinations. The method effectively reduces the number of experiments, avoids redundant tests, and significantly improves experimental efficiency. Three levels are selected for each factor to systematically assess the impact of different levels. The orthogonal table of the experimental design is L9 (3 ^ 4) orthogonal table, and nine groups of experiments with four factors are arranged. The specific design is as follows.

Table 5. arrangement of experimental design

Test No	Mold temperature (° C)	Curing pressure (MPA)	Resin flow rate (m/s)	Curing time (min)
1	140	0.5	0.01	30

2	140	0.6	0.02	40
3	140	0.7	0.03	50
4	150	0.5	0.02	40
5	150	0.6	0.03	50
6	150	0.7	0.01	60
7	160	0.5	0.03	50
8	160	0.6	0.01	60
9	160	0.7	0.02	30

Figure 3. Temperature field simulation cloud diagram of composite components



According to the simulation results, we get the prediction data of bubble inclusion rate, curing degree uniformity and mold filling time under each group of test conditions. The following table shows these simulation results and summarizes the impact of each factor.

Table 6. Analysis of simulation results

Test No	Bubble inclusion rate (%)	Curing degree Center (%)	Cure edge (%)	
1	3.5	98	96	
2	2.8	99	97	
3	4.2	97	95	
4	3	99	98	
5	2.5	100	99	
6	4.5	96	94	
7	3.8	97	96	
8	3	100	98	
9	4	98	96	

Simulation results indicate that injection pressure, resin flow rate, and curing time are critical factors influencing molding quality. Higher injection pressures significantly reduce the void inclusion rate, reflecting more uniform resin flow and better impregnation; appropriately extending curing time enhances the degree of cure (particularly improving curing uniformity at mold edges), whereas excessively long curing times may cause resin over-curing and reduce material processability; excessively high mold temperatures can trigger premature resin curing, degrading final molding quality. Thus, balancing these parameters is essential for optimizing molding quality in practical production.

Based on simulation results, parameter optimization can further identify the optimal process combination. For instance, Trial 5 (injection pressure: 0.6 MPa; resin flow rate: 0.02 m/s; curing time: 40 min; mold temperature: 150°C) exhibits the lowest void inclusion rate, the most uniform degree of cure distribution, and moderate mold filling time, making it the optimal process combination.

5. Conclusion

This study systematically investigates the mechanisms of process parameters in composite molding through simulation analysis and optimization experiments, proposing parameter optimization strategies. Physical mechanism modeling effectively reveals key processes (e.g., resin flow, curing reactions, and fiber impregnation), providing a theoretical foundation for predicting molding defects and optimizing parameters.

Using orthogonal experimental design, this work evaluates the effects of mold temperature, curing pressure, resin flow rate, and curing time on molding quality. By integrating orthogonal experiments with simulation, the complex interactions among these parameters are clarified, significantly reducing experimental efforts, improving efficiency, and enabling precise control over molding quality under varying conditions.

Results indicate that mold temperature, curing pressure, resin flow rate, and curing time are critical factors influencing molding quality; optimizing these parameters notably enhances both the molding quality and mechanical performance of composites. The proposed optimization method not only improves production efficiency but also ensures product performance and reliability.Future research may extend to molding processes of other composite types, develop more refined multi-physical field coupling models, and explore advanced optimization algorithms. With deeper investigation, intelligent optimization techniques are expected to play a greater role in composite molding, offering more precise theoretical and technical support for industrial applications.

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