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Optimization Study of Porosity Problem in Hand Gluing Process Based on TRIZ Theory

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Abstract: *In order to meet the development of composite materials in the aerospace field of replacement. Aiming at the carbon fiber composite material preparation process in the hand-layup molding process molding parts porosity is too large, the mechanical properties of the parts is low and other problems. This paper introduces TRIZ theory to analyze the problematic conflicts in the hand-layup molding process.The problems are decomposed into components and logically connected before and after, and the problems are analyzed by applying innovative thinking to system analysis, including functional analysis, cause and effect analysis, and the nine-screen analysis method. Then the final ideal solution, ARIZ algorithm, and contradiction matrix in TRIZ tool are applied to derive an innovative and optimized solution in conjunction with the steps of the hand lay-up molding process. Ultimately, the goal of reducing porosity and applying it to modern hand lay-up molding composites is achieved.*

Keywords: *TRIZ theory; Hand Lay-Up; Carbon Fiber Composite Material; Innovative Optimization*

1. Introduction

With the development of composite material technology, the utilization rate of carbon fiber composites in aircraft structures has been increasing. The large adoption of carbon fiber composite components plays a significant role in reducing aircraft weight, lowering fuel consumption, extending aircraft maintenance cycles, and improving aircraft performance [1,2].

The hand-lay-up molding process, as one of the methods for molding thermoset resin matrix composites, is the simplest, most economical and effective molding process.Only a few tools are needed to achieve the operation, molding is not limited by the size and shape of the product, the production technology is easy to master, easy to meet the needs of product design, the products have a high resin content and good corrosion resistance[3].However, as a traditional preparation process, this method is inefficient and has a long production cycle; the quality of the finished product is not easy to control and the performance stability is poor with low mechanical properties[4].In the preparation process, it needs for a large number of people to operate.At the same time, due to the actual operation of the workers will inevitably produce errors. This will lead to differences in the quality of the manufactured parts, and ultimately make the finished parts too large pores, high porosity[5].

Generally speaking, composites in aerospace field pursue lightweighting. In order to avoid making the material itself produce quality problems in this process, we need to carry out research to reduce the porosity[6].However, hand lay-up molding has been developed as a traditional composite molding process so far, and even though the porosity of the material is high due to low-temperature and low-pressure molding, there are still a large number of developing countries that use hand lay-up molding as the main FRP production method [7]. It seems that as times change, more and more other process steps will be introduced into the hand-paste molding process to assist in meeting the performance requirements and to continually help upgrade the preparation process.

Currently TRIZ theory, as an invention method solution theory, summarizes the approach to solving innovation problems into 39 inventive principles, each of which provides a method for solving a specific type of problem [8].It is a methodology that is used to propose innovative solutions, creates systematic innovations and helps improve the designer's thinking process. Through the complete process of posing problems, analyzing problems, applying methods, and solving methods, the root cause of the problem is gradually analyzed in depth. It helps researchers to discover the root of the problem and propose solutions more quickly and accurately. At present, this method has been applied in more and more fields of scientific research and exploration and is developing towards diversification [9]. And more and more successful cases show the development and potential of TRIZ theory in engineering research [10].

2. Problem description and analysis

At present, the preparation of carbon fiber composites in small composite material applications such as the General Aviation Research Institute are applied to the preparation of carbon fiber composites by hand-lay-up molding. However, during the preparation of carbon fiber composites, the porosity is increased because part of the gas cannot escape and remains in the parts.Therefore, how to reduce the porosity of molded composite parts and improve their mechanical properties is a major part of composite molding research.[11].

The generation of porosity mainly affects the mechanical properties of the parts such as shear strength, bending, tensile and compressive strength and modulus of mechanical properties [12]. Based on this, this paper analyzes the influence of this system in the preparation process of composite materials and proposes solutions to facilitate the experimental testing, and ultimately achieve the expected results of the optimal design of composite hand-lay-up molding.

3. Analysis using TRIZ tools

3.1. Functional analysis

Applying TRIZ theory to describe this problem, a functional model is established as in Fig. 1. Focusing on the key functions and objectives of the hand-lay-up molding process, a systematic collation of the functional components is carried out and how to improve and optimize the complete process is explored.

In order to come up with the following five final requirements for process optimization: ① Improve product quality ② Enhance product performance ③ Improve process stability ④ Reduce scrap output rate ⑤ Reduce cost problems caused by material waste. Combined with the process preparation flow procedures, the functional components in different processes are listed as follows: epoxy resin, carbon fiber, air, workers, vacuum bags, release cloth, felt, oven, etc.The function of the system is analyzed in terms of the relationship fit between the components and the stakes, and the insufficient and harmful roles are analyzed in it, as shown in Fig. 1.

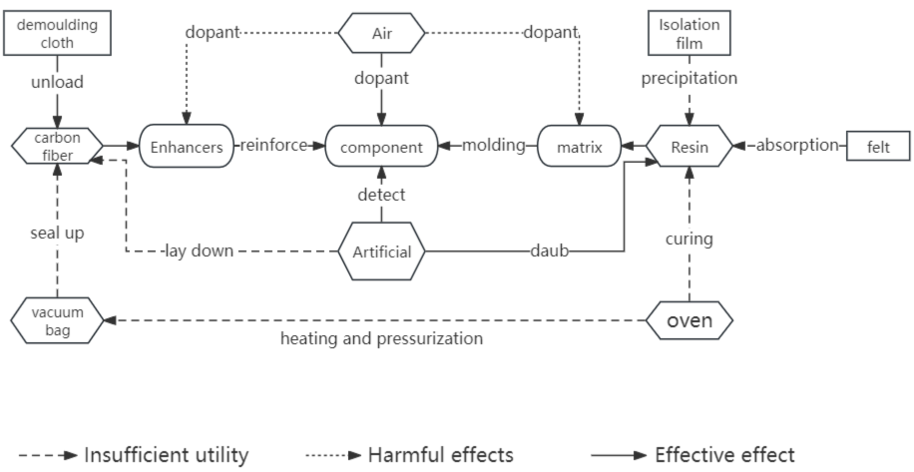

Figure. 1 Functional flow chart of optimized hand-lay-up molding process

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3.2. Causal analysis

The step components affecting porosity in the fabrication process were initially identified from the component function analysis, but the root cause could not be determined.Therefore, a chain of causal analysis is constructed through causal analysis to point out the causes of porosity problems and the results that lead to the problems.

As shown in Fig 2, the reasons for the high porosity are ① Air entrapped in the layup process: It may be due to improper operation, high ambient humidity or the material itself. ② Moisture absorption: Absorption of moisture into the material during storage or handling may result in the release of moisture to form pores during the curing process. ③ Gases generated during curing: Certain additives or the material itself may release gases during the curing process. ④ Inadequate resin flow and incomplete wetting: It may be due to high material viscosity, improper temperature control or insufficient pressure.

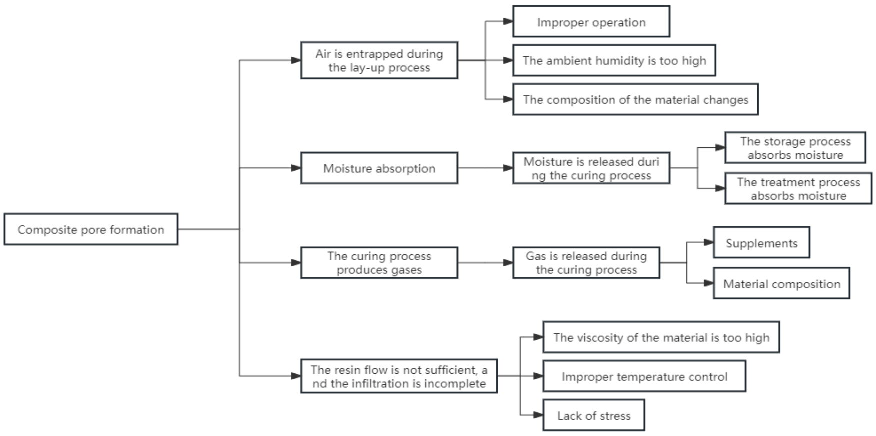

Figure. 2 Cause and effect analysis diagram for optimizing the hand lay-up molding proces

3.3. Nine-screen analysis

According to the nine-screen analysis method, raw materials, molds, layups, curing, and testing are considered as subsystems, and carbon fiber composites are considered as supersystems.The subsystem changes the process to prepare materials with low porosity in accordance with the law of evolution for improving the ideal as in Fig. 3.

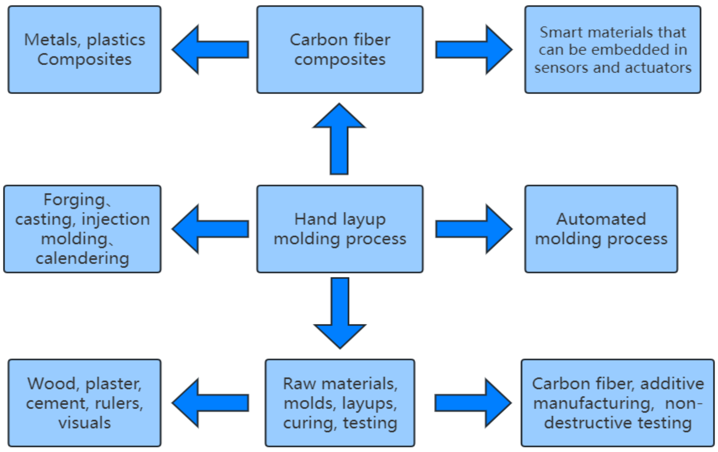

Figure 3 Nine-screen analysis diagram

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4. Using TRIZ tools to solve

4.1. Deriving solutions from the final ideal solution

Based on the above results of the system analysis based on TRIZ theory, the following two solutions are obtained by using the Final Ideal Solution analysis as shown in Table 1

Table 1 Final ideal solution analysis process

Question	Analysis of the results	
What is the ultimate goal of design?	Optimization of material properties to ensure stability and safety in a variety of applications	Improvement of part densities, specific;strength/stiffness/functionality enhancement
What is the ideal solution?	Reduces material porosity, improves mechanical properties and service life of materials	Breathable film helps to expel volatile matter pressure during the curing process;Ultrasound facilitates the reduction of nanoparticle agglomeration and the improvement of nanoparticle pull-out distribution
What are the barriers to achieving the final desired outcome?	Gas overflow obstruction, fiber aggregation obstruction, resin flow obstruction	Breathable membrane can increase the channels for gas spillage and help to release the gas; The application of ultrasonic vibration allows for uniform fiber dispersion
Why it can be an obstacle for you?	Internally generated gases cannot be effectively vented and are trapped inside the material	The use of breathable membrane or ultrasonic vibration method, can effectively remove gas, and improve the performance of the compound table material
Can other tools fix this?	Hot pressing, vacuum-assisted resin transfer molding, nano-focused computed tomography (micro-CT)	High cost and long weekly peers are not favorable to economic efficiency

Option 1:Based on this process, a layer of PVA breathable film is placed above the absorbent felt and below the vacuum bag in order to achieve the demand of overgassing and non-resin.Improves the efficiency of gas extraction inside the vacuum bag while retaining excess resin in the absorbent felt.

Option 2: At the end of the lay-up of the manufactured parts, the above preformed fiberboard was sealed with cling film.Slowly submerge it in water for ultrasonic vibration-assisted infiltration.Unwinding of agglomerated fibers by ultrasound to improve fiber distribution and thus adequate diffusion[13].

4.2. Derivation of the program according to the ARIZ algorithm

Follow the core steps of the ARIZ algorithm for optimal design, combined with the above system analysis in the system analysis of the conclusions obtained.First of all, clarify the problem for the hand-lay-up molding process and porosity to produce more direct conflict and then analyze the problem and the problem constraints, etc. in order to build the problem model in Fig4,，to get the following two solutions.

Option 3: Suitable cure cycles and cure times were explored by controlling material factors, temperature gradients and cure times.This in turn maximizes the thermal and mechanical properties of the matrix and enhances the resin properties.

Option 4: After sealing the parts, molds, etc. in a vacuum bag,.The vacuum pressure is varied to determine how much pressure to provide to squeeze the flow of resin between the fiber layers, and how much pressure to provide to fill the gaps between them with minimal cost.

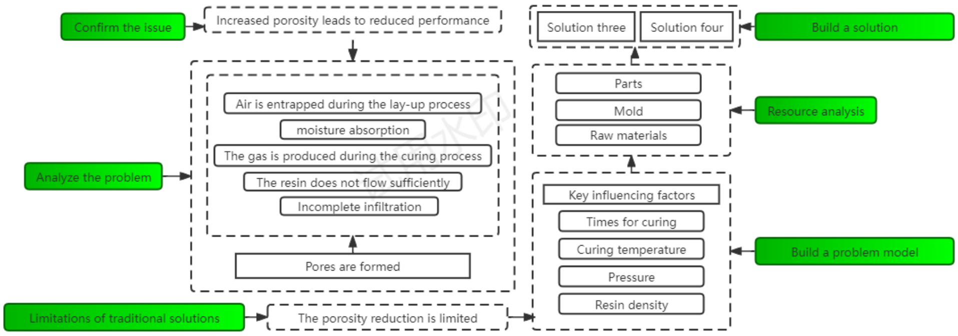

Figure 4 Analysis process of ARIZ algorithm

4.3. Programs based on technical contradictions

According to TRIZ theory, explore the conflicts in this process optimization problem.And determine the relationship between the complexity of the system in terms of the deterioration parameter and strength of parts as a parameter to be improved. Referring to the conflict matrix provided by TRIZ theory, apply the 2 Extraction Principle, 15 Dynamic Principle, and 17 Multi-Dimensional Operation Principle components of the Invention Principle to the conflict matrix.

Table 2 Contradiction matrix

Deteriorating parameters / Improved parameters	Complexity of the system
Dissociation	2 Extraction Principle 15 Dynamic Principles 17 Principles of Multidimensional Operation

Following the core idea of each principle, the No2.extraction principle expresses the extraction of harmful components from the system to improve system performance; No15.expresses the introduction of dynamic factors that cause the system to change under certain conditions;No17 expresses performing operations in multiple dimensions simultaneously or sequentially. Integration into the optimization of this molding process resulted in two scenarios

Option 5: Exhaustion of volatiles from inside the material during the preparation process. By adding a gas conduction path, the “interlayer” gas conduction between the material and the release cloth at the edge of the part is adapted to the “in-face” gas conduction between the resin and the dry fibers.

Option 6: By encapsulating two layers of vacuum bags and placing a perforated steel divider between them. Initially, both layers of vacuum bags are connected to the vacuum system. At this time, the parts are in a vacuum state to accelerate the gas overflow without bearing the compression force. Subsequently, after canceling the outer vacuum, the inner vacuum bag is pressed into the surface of the part for further molding.[14].

5. Conclusions

This paper takes aerospace composites as an example, for the process application problems of hand-lay-up molding, based on multiple analysis methods of TRIZ theory as well as problem solving approaches, eight solutions to the optimization problems are finally proposed. These include PVA breathable film application, ultrasonic vibration application, curing time and temperature problem, vacuum air pressure problem, air conduction path problem, and double vacuum bag application. The combined application of these improvements is designed to optimize the traditional hand lay-up preparation process, thereby improving part quality and reducing porosity. The eight applications will be evaluated on the basis of conflict resolution, complexity, cost, feasibility, and stability. It is hoped that the optimal solution will be reached in order to achieve an implementable solution for the optimization of the hand lay-up molding process.

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