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Optimization design of support structure diaphragms of composite forming die integrated with response surface

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Abstract. Although mold designs are used in various sectors, molding composite materials results in issues such as deformation and insufficient stiffness. To this end, the response surface method was used to optimize the design of the mold support structure partition, improving the performance parameters of the mold by increasing the number of U and V direction partitions. The experiment showed that the deformation during forklift transportation decreased by 36.5%, during lifting transportation by 13.9%, during paving deformation by 36.9%, and during hot pressing, the deformation of the tank was reduced by 18.2%. After optimization, the maximum deformation of the mold under conditions such as forklift transportation, lifting, and paving is similar to or slightly reduced from the original model. Meanwhile, the thermal deformation and quality of the mold decreased by 28% and 12.8%, respectively. The research results have important reference value for the design of composite material forming molds, helping to improve the performance and efficiency of the molds and reduce costs. By optimizing the design of the support structure partition, effective control of mold deformation can be achieved, and the stiffness of the mold can be improved, thereby ensuring the stability and reliability of the mold under various working conditions.

Keywords: Response surface / composite materials / forming mold / supporting structure / partition optimization

1 Introduction

The application of composite materials in high-tech industries is becoming increasingly widespread, especially in fields such as aerospace, automotive manufacturing, and energy development. Its superior mechanical and physical properties make it an ideal choice. Especially in the design of composite forming molds, their excellent heat resistance, corrosion resistance, and fatigue resistance provide reliable guarantees for various high-precision equipment [1,2]. The internal structure design of composite material forming molds directly affects their comprehensive performance. Traditional design does not consider the actual stress distribution and heat conduction in the support structure and partition design, which affects the service life of the mold and also affects the forming quality [3,4]. Optimizing the design of mold support structure and partition design, with the aim of improving the actual performance of the mold, has become an urgent problem in the field of engineering technology. The application of response surface methodology to optimize the support structure and partition design of composite material forming molds can effectively solve the internal structural design problems of the molds. This method is on the ground of experimental design and mathematical modeling, and obtains the optimal solution by establishing an objective function and constraint conditions [5]. The optimized mold support structure and partition design will be adjusted on the ground of actual stress distribution and heat conduction to improve the mold's service life and molding quality. This method could have a significant impact on the design and use of composite material molds, promoting the development of high-tech industries. The study aims to explore the design of composite material molds from a new perspective and verify the feasibility of optimized design through empirical and theoretical verification. The innovation of this work lies in the application of response surface methodology to the design of support structures and partitions for composite material molds. This provides new ideas and methods for mold design. The contribution of research lies in improving the lifespan and forming quality of molds, providing theoretical support, solving design problems, and laying the foundation for the development of composite materials and engineering technology progress. The research will be carried out in four parts. The first part is an overview of the optimization design of composite material forming mold support structure partitions

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incorporating response surfaces. The second part is a model for optimizing the design of composite material forming mold support structure partitions incorporating response surfaces. The third part is the experimental verification of the second part. The fourth part is a summary of the research content and points out the shortcomings.

2 Related works

Composite material forming mold design plays a crucial role in many industries, and the optimization of its support structure and partition design directly affects the service life and forming quality of the mold. Hussin et al. proposed the application trend of rapid tooling technology in the production of mixed mold inserts. The research results showed that the use of mixed mold inserts made of metal epoxy composite materials can improve the speed and performance of mold development. It not only provided relevant information and highlights the gaps in current research, but also evaluated the new formulations of metal epoxy composite materials for mixed mold inserts used in injection molding applications and rapid molds for non-metallic products [6]. Denis et al. explored and compared new phenomena related to the consolidation of thermoplastic composite materials in ovens/autoclaves. This study found that the contact thermal resistance between molds and parts, as well as the influence of mold geometry, become important and require physical explanation. The experimental method was compared with numerical simulations of heat transfer and crystallization, verifying the proposed thermodynamic model [7]. Wu et al. added carbon fibers to SKD61 tool steel to produce high thermal conductivity composite materials. Chemical copper plating inhibited the reaction between carbon fibers and steel. The results indicated that the obtained carbon fiber/SKD61 composite material has high density. Copper plated carbon fibers act as sintering promoters, while copper prevents direct reaction between carbon and steel [8]. Ouezgan A's research team covered and adhered the mold with a vacuum bag, and then evacuated it using a vacuum pump. The preforms were impregnated with resin under atmospheric pressure. Numerical simulations were conducted on four main manufacturing routes, and it was found that the fourth route, which involves injecting resin first and then vacuuming, is the most efficient, reducing processing time by 19.9% [9]. Kumar et al. proposed and designed a dual frequency magnetically insulated line oscillator. The beam wave interaction behavior and device RF output performance of a typical diode at a voltage of 550 kV and a current of 48 kA were studied through three-dimensional particle simulation. The simulation results indicated that the proposed MILO generates approximately 3.5 GW of RF peak power at frequencies of 3.62 GHz and 3.72 GHz. The conversion efficiency of this device is approximately 13.25% [10].

As an effective optimization method, the application of response surface methodology in the design of composite material forming molds provides new ideas and methods for solving problems in traditional design. Yan et al. proposed a three-dimensional ablation model considering surface and volume ablation of LQP composite materials, which is used to predict the thermal response of materials in aerodynamic high-temperature environments. The research results indicated that radiation and thermal barrier effects are the main mechanisms for the ablation resistance of LQP composite materials, and the low thermal conductivity determines their insulation performance. By adjusting the material composition and surface treatment, the surface temperature of the material can be reduced and the ablation resistance can be improved [11]. Diniz et al. proposed the use of finite element (FE) methods and experimental design statistical methods to optimize the position of ply descent in laminated structures with ply reduction. The research results indicated that not all design factors affect changes in response variables, and strain and natural frequency response variables are highly significant. The optimization results revealed that the optimal landing position for minimizing strain and maximizing natural frequency is the end landing. This study considered both horizontal and vertical positions and identified the most important design variables related to the position of the ply descent [12]. Gong et al. proposed a micro electric discharge machining method for Cf ZrB2 SiC composite materials with excellent performance. The research results indicated that micro electric discharge machining can effectively remove this hard and brittle material, and kerosene is the optimal processing medium. By optimizing the combination of process parameters, good surface quality and high processing efficiency can be achieved. This method provided a feasible approach for the secondary processing of hard and brittle materials [13]. Keramat et al. established a model using central composite design (CCD) and response surface methodology to optimize the mechanical properties of sintered Al2O3. The research results indicated that sintering temperature, Al2O3 particle size, lubricant and eutectic content are key variables. By optimizing these variables, the fracture strength and density of Al2O3 can be maximized [14]. Vasanthkumar P's research team studied the wear behavior of shell particle reinforced thermoplastic polymer (nylon 6). They used response surface methodology and grey wolf optimization algorithm to optimize interface temperature, wear loss, and friction coefficient. The research results indicated that rotational speed and shell particle content significantly affect interface temperature and wear loss. The rotational speed and shell particle content also significantly affected the friction coefficient [15].

In summary, this study focuses on optimizing the design of mold support structures and partitions through the application of response surface methodology, providing a new path to break through traditional design. Although there are limitations in dealing with the stress distribution and heat conduction response of different composite materials, it provides valuable reference for composite material mold design. The research is expected to promote further research and development in related fields, and has practical application potential in fields such as aerospace, automotive manufacturing, and energy development. It is expected to play a greater role in practice in the future.

3 Optimization design model for support structure partition of composite material forming mold integrating response surface

The optimization model for composite material forming molds incorporating response surfaces is divided into two parts: support structure and partition optimization, and size optimization. Firstly, it establishes an optimization model for the support structure and partition, taking into account the characteristics of composite materials and key forming factors. Next, by incorporating the response surface method for size optimization, the maximum performance of the mold is achieved. This method is expected to provide new ideas for the optimization design of composite material forming molds.

3.1 Optimization model for support structure partition of composite material forming mold

The optimization model for composite mold support partitions is on the ground of a deep understanding of the characteristics and forming process of composite materials, taking into account key factors such as heat conduction and stress distribution. This can effectively guide mold optimization design, and is expected to improve performance and molding effect. Topology optimization optimizes objectives under constraints and load conditions by pruning and redistributing materials to reduce material usage and costs or maximize performance [16,17]. It is divided into continuum topology optimization and dispersion topology optimization, with the former suitable for continuous objects and a wide range of applications. There are two main methods for optimizing continuum structures: one is to optimize by changing material properties, such as homogenization method and variable density method. The second method is to change the geometric shape, such as variable thickness method, independent continuous mapping method, etc. The variable density method is a more reasonable method for establishing a topology optimization mathematical model in this paper. To determine the optimal design of the mold support structure partition, a multi-objective genetic algorithm is implemented. This algorithm aims to handle multiple objectives, such as minimizing weight while maximizing strength and thermal stability. The input data for this algorithm comes from a series of FE simulations of composite material forming processes. These simulations provide a detailed analysis of material behavior under various forming conditions. This analysis is crucial for determining constraints and optimization targets. Parameters such as pressure distribution, temperature gradient, and cooling rate can be extracted from FE simulations and used as input data to effectively evaluate and optimize baffle design using genetic algorithms.

In order to optimize the support structure of the forming mold, it is essential to have a clear understanding of the working conditions. A thorough analysis has been conducted to quantify the forces applied to the mold during the forming process, which typically range from [insert specific force range] depending on the size and geometry of the composite being formed. The temperature conditions are closely monitored and controlled during the forming process. The mold surface temperature varies between [insert specific temperature range] to ensure optimal curing of the composite material. These working conditions are factored into the response surface model to optimize the design of the partition plate, ensuring that it can withstand the operational stresses and thermal cycles. The mathematical model expression is shown in equation (1).

$$\begin{cases} \underset{\rho(x_i)}{M\,\text{in}}\, f(\rho(x_i)) \\ s.t. \int_{\Omega} \rho(x_i) d\Omega \leq \overline{V} \\ \quad \rho(x_i) = 0 or 1, \forall x_i \in \Omega \end{cases} . \tag{1}$$

In equation (1), Ω is the initial design space, Ω_{mat} is the optimized design domain, $\overline{\mathrm{V}}$ is the material usage constraint, f is the objective function, and $\rho(x_i)$ is the material density function. The specific expression of $\rho(x_i)$ is shown in equation (2).

$$\rho(x_i) = \begin{cases} 1 & \text{if } x_i \in \Omega_{mat} \\ 0 & \text{if } x_i \in \Omega/\Omega_{mat} \end{cases} . \tag{2}$$

In equation (2), x_i is the pseudo density value of each element after Ω is discretized into n FEs. The variable density method aims to minimize flexibility (i.e. maximize stiffness), so the transformed mathematical model is shown in equation (3).

$$\begin{cases} \underset{x}{Min} & C = \frac{1}{2} F^T U \\ s.t. & KU = F \\ & V(x) = \sum_{i=1}^{n} x_i v_i \leq V \\ & 0 < \delta \leq x_i \leq 1, i = 1, 2, 3, K, n \end{cases} . \tag{3}$$

In equation (3), v_i is the volume of the i-th unit, V is the total volume of the optimized area, and δ is the minimum unit density. Topology optimization software such as Optistruct and Tosca commonly use variable density methods. Optistruct requires Hypermesh preprocessing, while Tosca, acquired by Dassault System, integrates ABAQUS, SIMULIA, etc., which can solve checkerboard problems and enhance engineering significance. Topology optimization takes solid plates as the initial design space, and removes some materials to achieve the optimization goal. Although existing methods often target a single operating condition, engineering problems often involve multiple operating conditions. For multiple working conditions, they are usually decomposed into single working conditions and weight ratios are set for each working condition, but the setting method is arbitrary and lacks a unified method. Referring to the analytic hierarchy process in operations research, it calculates the weight ratio of each operating condition to solve the topology optimization problem of multiple operating conditions. The hierarchical model for topology optimization under multiple operating conditions is shown in Figure 1.

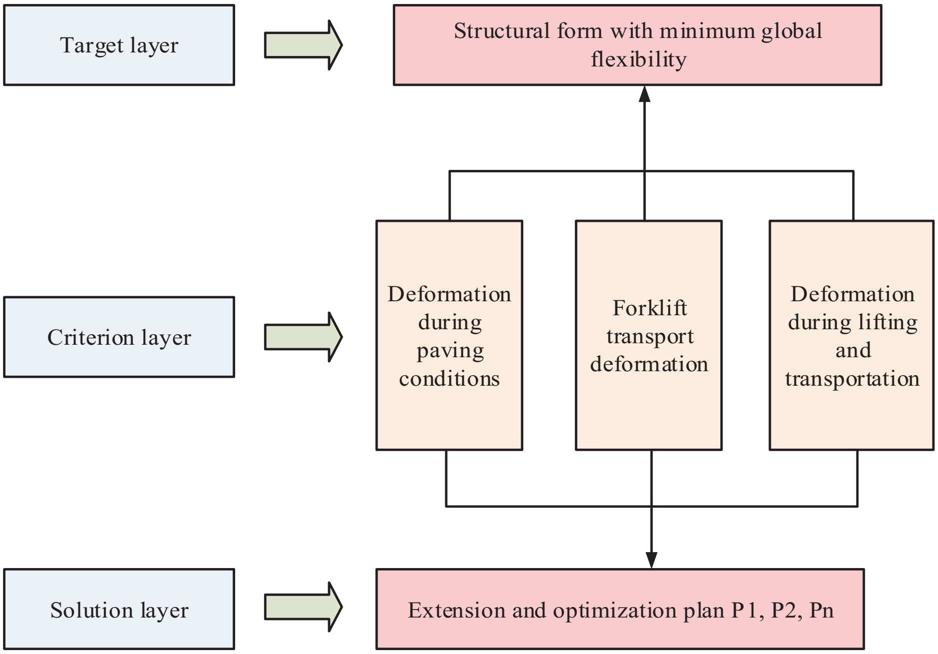


Fig. 1. A hierarchical model for topological optimization of multiple operating conditions.

In Figure 1, the complex multi-objective decision-making problem is decomposed into multiple levels. It judges the relative importance of each goal and standard through experience, and determines the weight of each standard. Then it makes systematic decisions for multi indicator and multi scheme optimization.

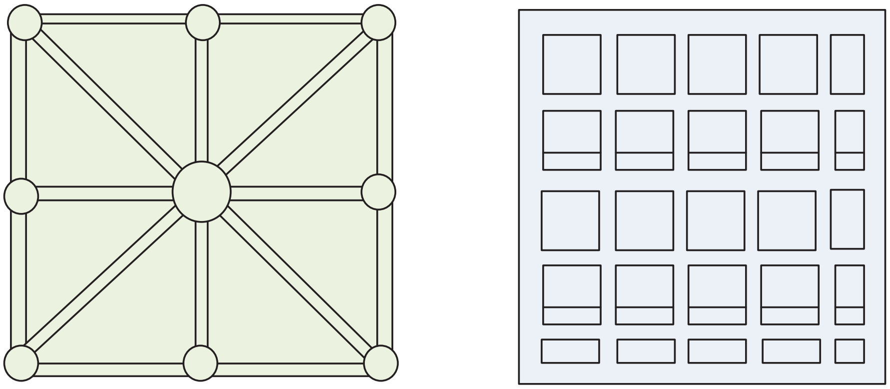
For mold hot pressing forming, the temperature field and thermal deformation are calculated first. This is a topology optimization working condition with high computational complexity and is prone to errors. Therefore, the optimization process only aims to achieve the best stiffness, which is the minimum structural flexibility. Thermal deformation is not considered. Multiple operating conditions are decomposed into a single objective using linear weighting method, with constraints on the volume ratio of each operating condition and mold deformation. After optimization, it conducts temperature field and thermal deformation calculations for verification and comparison. The topology optimization mathematical model for multiple operating conditions is shown in equation (4).

$$\begin{cases} MinC(\rho) = \sum_{i=1}^{m}\alpha_i C_i(\rho) \\ s.t.\begin{cases} \sum_{i=1}^{m}\left(\sum_{j=1}^{n}V_j\right) - \overline{V} \le 0 \\ 0< \rho_{\min} < \rho_j < 1 \\ d_{pi}^L < d_{pi} < d_{pi}^U \end{cases} \end{cases} . \tag{4}$$

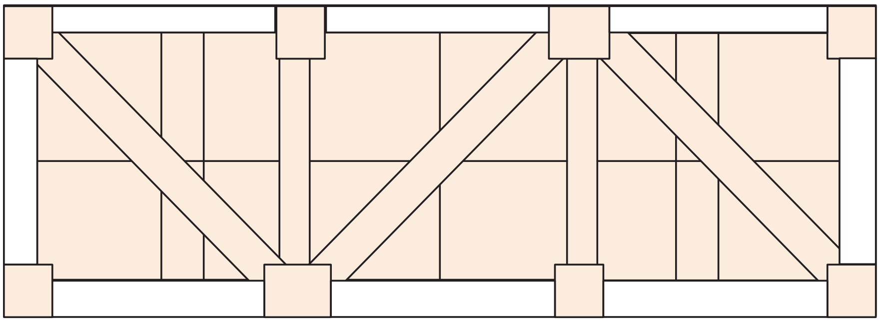
In equation (4), $C_i(\rho)$ is the sub flexibility objective function for the i-th working condition. ρ_j is the design variable. m is the total number of load cases. n is the total number of units. V_j is the volume of the j-th unit. j is the maximum volume of the design space. d_{pi} is the displacement of node p under the i-th working condition. d_{pi}^L and d_{pi}^U are the upper and lower limits of displacement, respectively. After determining the importance scale between each two working conditions, an ideal pairing comparison matrix can be established, as shown in equation (5).

$$M = \begin{bmatrix} a_1/a_1 & a_1/a_2 & L & a_1/a_n \\ a_2/a_1 & a_2/a_2 & L & a_2/a_n \\ M & M & M & M \\ a_n/a_1 & a_n/a_2 & L & a_n/a_n \end{bmatrix}. \tag{5}$$

In equation (5), the eigenvector of matrix M is $a = [a_1, a_2, K, a_n]^T$. The mold support structure consists of a partition and a bottom plate frame, which has a significant impact on the mold stiffness. In the past, research on mechanical properties focused more on the influence of partition parameters such as thickness and ventilation hole edge distance, and less on bottom plate frames. However, it is important to note that the layout of the bottom plate frame is also crucial for the mechanical properties of the mold, in addition to the thickness of the bottom plate. There are various forms of bottom plate frames, such as central radial, vertical and horizontal chessboard, and diagonal reinforcement, and their optimized design is worth further research. The bottom frame form is shown in Figure 2.



(a) Central radialTraining Prediction (b) Checkerboard format



(c) Oblique reinforced plate type

Fig. 2. Bottom frame form.

In Figure 2, for the research object of the mold, the optimal bottom frame form is predetermined. The form of the bottom plate has no fixed parameter expression and cannot be optimized using the response surface method, while the form of the bottom plate affects the stiffness of the mold. Using ABAQUS software to optimize the base plate, its load module defines multiple operating conditions and integrates TOSCA module. The optimized area is the bottom plate, while the non-optimized area includes the bottom plate frame, support structure, and shaped plate. The frame is designated for welding and serves to establish the assembly body, material properties, and section properties. The mesh division used is tetrahedral with a unit type of C3D10, a global seed edge length of approximately 50 mm, and a maximum deviation factor of 0.1. The working conditions for paving, lifting, and forklift transportation are defined, and design responses for displacement, volume, and strain energy are established. Weight ratios are set, and the bottom plate structure is optimized. The strain energy is inversely proportional to the stiffness, and its specific formula is shown in equation (6).

$$C = \sum_{i} C_i = \frac{1}{2} U^T K U. \tag{6}$$

In equation (6), K is the stiffness matrix, and U is the displacement matrix of the element node. To improve the rigidity and heat dissipation of the mold, the ventilation holes on the support partition have various shapes, which affect the performance of the mold. Therefore, it is necessary to optimize the selection. Structural optimization can be achieved through methods such as size, shape, and topology. Topology optimization is more reasonable for shape optimization of ventilation holes, as it allows for irregular shapes. The initial rectangular ventilation hole mold is imported and a solid filling plate is established on the ground of the hole shape. The areas are then divided into optimized and non-optimized areas for subsequent optimization. The final optimization result of the ventilation hole pattern is shown in Figure 3.

3.2 Optimization model for composite material forming mold size integrating response surface

Introducing the response surface method for mold size optimization is an important step after optimizing the support structure and partition. Response surface methodology, as an optimization tool, effectively handles multivariable and multi-objective optimization problems.

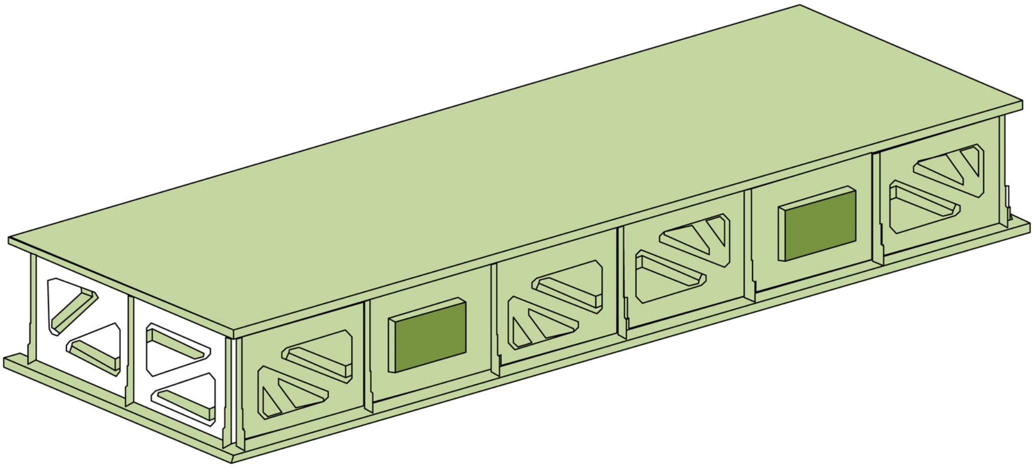


Fig. 3. Final form of ventilation hole optimization.

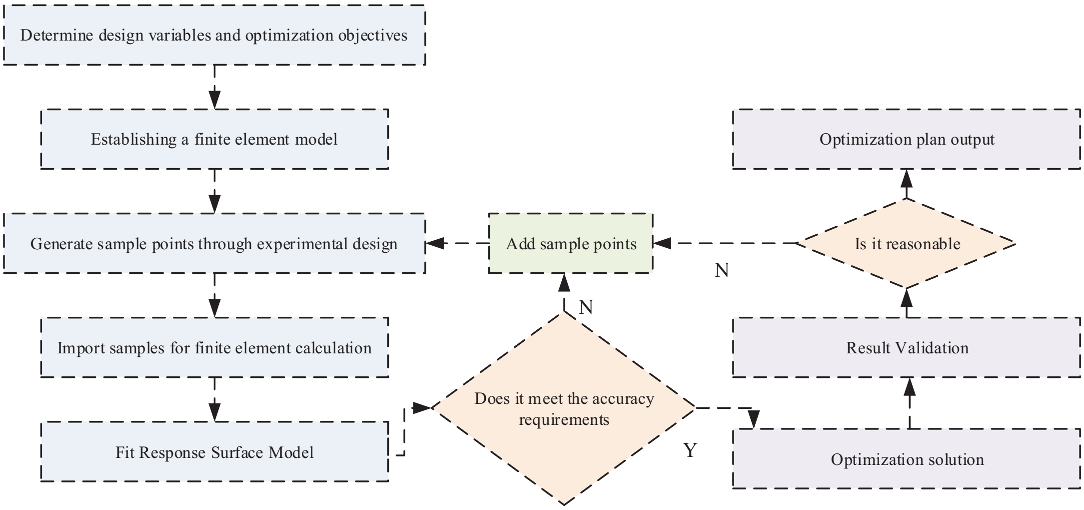


Fig. 4. Response surface optimization flowchart.

Therefore, a mold size optimization model incorporating response surfaces has emerged. This model aims to maximize the performance of the mold by adjusting the mold size, thereby improving the molding effect of composite materials. The response surface optimization flowchart is shown in Figure 4.

In Figure 4, the response surface model is optimized using experimental design and statistical theory to construct a fitting proxy model, simulate the relationship between design variables and performance indicators, and approximate it with expressions. To prepare composite material precursors, first weigh 1 mol/L epoxy resin and 0.5 mol/L curing agent and mix them in proportion. Then, use a high-temperature molding machine to shape the mixture at the preset temperature and pressure. Cure the formed sample at room temperature for 24 hours. Finally, clamp the cured composite material sample in a universal material testing machine and measure its size and performance indicators according to standard testing methods to construct a response surface model and complete mold size optimization. During the optimization process, all fitness values are calculated using a response surface model instead of FE simulation, saving computational time and costs. This model ensures a certain degree of accuracy and effectively optimizes the calculation process. The experimental design method is a systematic approach used to select appropriate design variables and factors and determine their interactions. This method can help designers avoid common errors such as overfitting or underfitting. Meanwhile, the experimental design method can also help designers determine which factors have a greater impact on performance indicators, thereby better guiding the optimization process.

When constructing a response surface model, it is usually necessary to collect some data to fit the model. These data can be obtained through experiments or actual measurements. After obtaining the data, designers can use statistical theory to fit the model and determine which factors have a greater impact on performance indicators [18,19]. Meanwhile, some software tools can also be used to assist in model fitting and data analysis. There are various types of response surface testing methods, with the most widely used being CCD and Box Behnken design. Among them, the number of central experiments of CCD makes

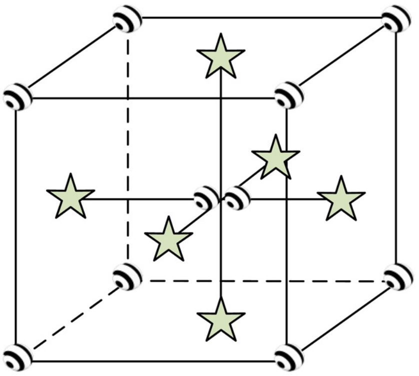


Fig. 5. Center composite surface design.

the overall design tend to be orthogonal, which is conducive to subsequent optimization. CCD, also known as quadratic regression rotation design, is suitable for fitting complete quadratic polynomial response surfaces and consists of a combination of full factor design, pivot point design, and center point design. The CCD formula is shown in equation (7).

$$\begin{array}{l} star_{upper} = base + (upper - baser) \times \alpha \\ star_{lower} = base - (base - lower) \times \alpha \end{array}. \quad (7)$$

In equation (7), *base* is the zero horizontal center point, *lower* is the lowest horizontal value, *upper* is the highest horizontal value, and α is the proportional factor. The central composite surface design is shown in Figure 5.

In Figure 5, in the central composite surface design, the α-axis point is located outside the cube design space, and the value of α depends on the actual experimental requirements. When α is 1, the axis point is located on the surface of the cubic design space, forming a central composite surface experimental design. The trend characteristics of each response change caused by changes in design variables are analyzed using a second-order response surface to construct an approximate model. The basic formula is shown in equation (8).

$$y| = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{i<1}^{n} a_{ij} x_i x_j + \varepsilon. \quad (8)$$

In equation (8), y is the optimization objective, a_0, a_i, a_{ii}, and a_{ij} are undetermined coefficients, x_i is the optimization variable, and ε is the accuracy error. The above equation is expressed using a matrix as shown in equation (9).

$$Y = XB + \varepsilon. \quad (9)$$

In equation (9), Y is the response value, X is the independent variable, and B is the unknown coefficient. It uses the least squares method to solve the unknown coefficient B, as shown in equation (10).

$$B = \left(X^T X\right)^{-1} X^T Y. \quad (10)$$

Before performing parameter optimization operations, the key step is to rigorously test the accuracy of the fitted response surface model. The main purpose of this verification process is to confirm the effectiveness of the model and ensure that it can serve as a reliable representative of real physical processes. The evaluation method for model fitting accuracy is to randomly select sample points within the design space and perform detailed calculations on these sample points. These calculations mainly include comparing the fitted values of the model and the FE calculation values. The FE calculation values are obtained by applying the FE method, which provides a relatively accurate reference point. In this way, the difference between model predictions and actual results can be quantified. To comprehensively and accurately evaluate the fitting accuracy of the model, certain statistical indicators need to be used. These indicators can reveal the performance of the model from multiple perspectives, helping researchers better understand and evaluate the advantages and disadvantages of the model. The regression equation is shown in equation (11).

$$\begin{cases} R^2 = 1 - \dfrac{\sum \left(Y_i - \widehat{Y}_i\right)^2}{\sum \left(Y_i - \overline{Y}\right)^2} \\ R_{Adj}^2 = 1 - \left(1 - R^2\right) \dfrac{n-1}{n-k} \end{cases}. \quad (11)$$

In equation (11), Y_i is the i-th observed response value, Y_i is the i-th fitted response value, Y is the average response value, n is the number of observed values, and k is the number of terms in the regression equation. Practical engineering problems are usually multi-objective optimization problems, where objectives may conflict with each other. Pareto solution is a solution that cannot improve any objective without weakening other objectives, and its objective function space is represented by the Pareto frontier. Multi objective genetic algorithm is an optimization method on the ground of genetic algorithm for Pareto frontier solutions. It was originally proposed by Fonseca in 1993, and later developed into multi-objective genetic algorithms such as NSGA, NCGA, AMGA, PE, etc. NSGA-II is an improved version of NSGA, introducing the concepts of “crowding distance” and “crowding distance sorting”, which can compare and sort Pareto solution sets within the same population generation to avoid getting stuck in local optimal solutions. The NSGA-II calculation flowchart is shown in Figure 6.

4 Optimization design analysis of composite material forming mold support structure partition plate incorporating response surface

The optimization design of the support structure partition of the composite material forming mold is analyzed, and the optimization effect is verified through theoretical analysis and experimental research. The optimization plan demonstrates its effectiveness. Subsequently, the performance comparison between the optimized mold and the

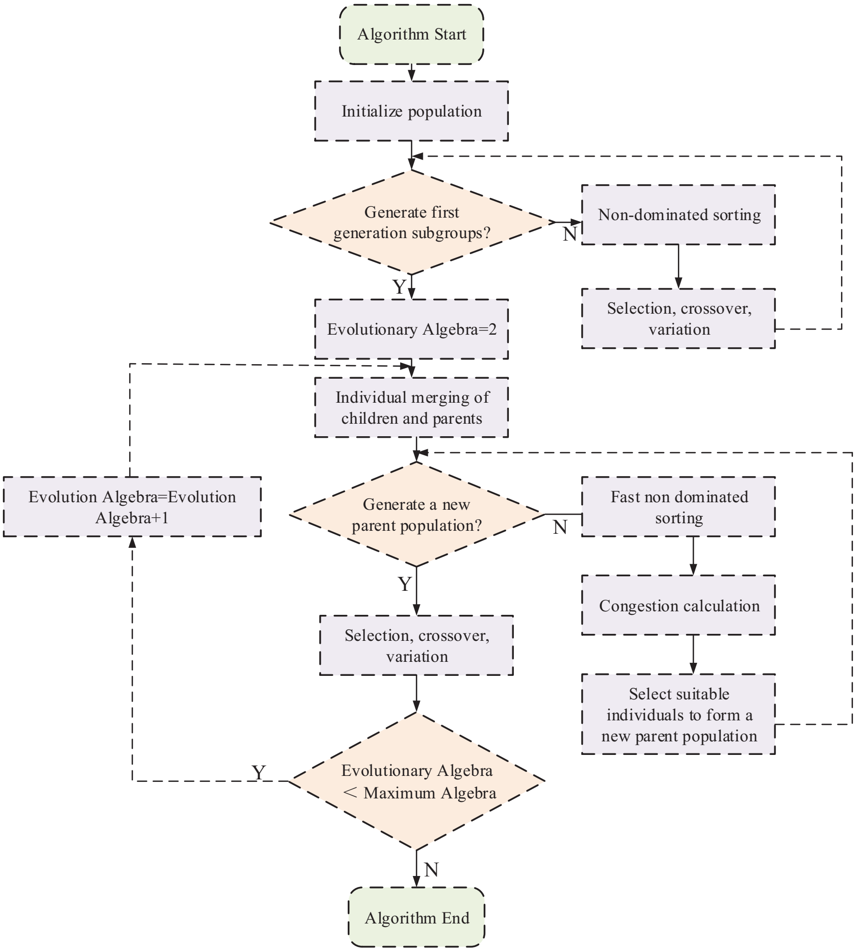


Fig. 6. NSGA-II calculation flowchart.

traditional mold is conducted. The mold incorporating response surface methodology is superior to traditional molds in terms of molding effect and mold strength, which provides an important reference for mold optimization design.

4.1 Analysis and optimization verification of support structure partition plate for composite material forming mold

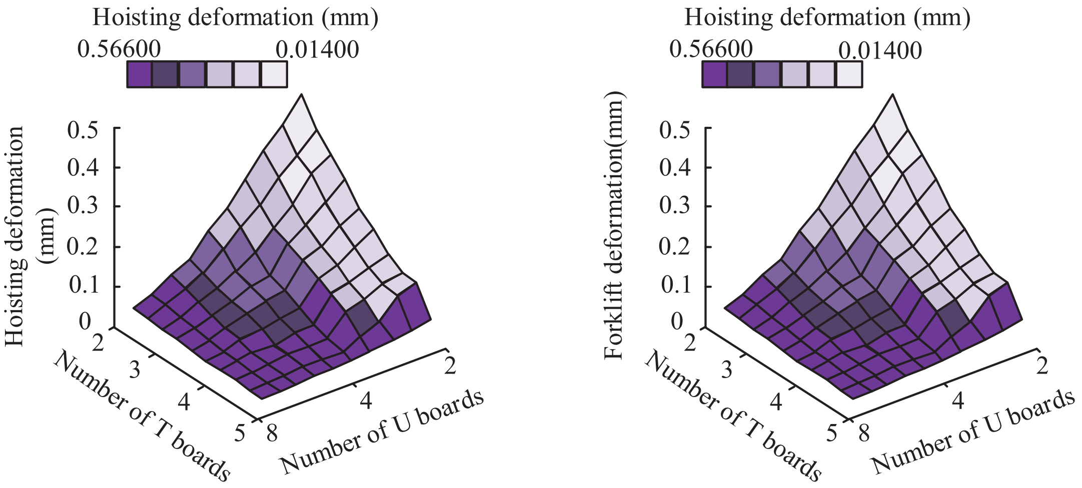
Detailed analysis and optimization verification are conducted on the support structure partition of composite material forming molds through experiments. Firstly, precise 3D modeling and FE analysis of the mold structure are achieved using SolidWorks 2018 and ANSYS 19.2. Subsequently, MATLAB R2018b conducts parameter optimization to optimize the mold structure. All calculations are performed on the Dell Precision 5540 computer, which has a main frequency of 2.6GHz and 16GB of memory. In addition, the Windows 10 Professional 64-bit operating system and Intel Core i7-9750H processor are used. The parameter settings of the model are shown in Table 1.

When parameterizing the mold, the number of U-direction (long side) partitions and V-direction (short side) partitions are used as design parameters. Referring to the aspect ratio of the mold, the parameter range of the U-direction partition is set to 2–5, and the parameter range of the V-direction partition is set to 2–10. It establishes deformation analysis for three working conditions in Ansys Workbench, with input parameters being the number of partitions and output parameters being the deformation of each working condition. The calculation results are shown in Figure 7.

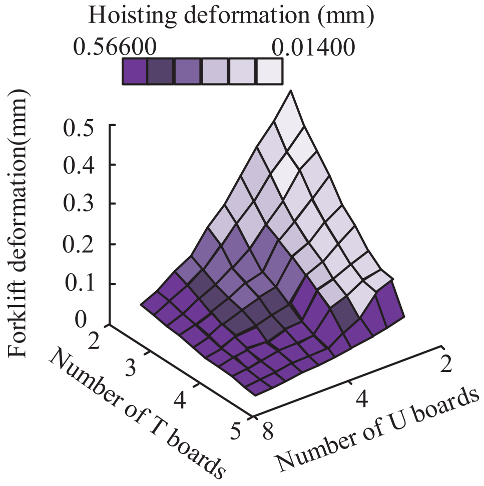
In Figure 7, as the number of partitions in the U and V directions increases, the deformation of the mold decreases and the stiffness increases. Specifically, when the number of V-shaped partitions increases to 3, the trend of deformation reduction approaches 0. When the number of U-shaped partitions increases to 7, the deformation reaches its lowest level. If the number of U-shaped partitions continues to increase, the increase in mold stiffness due to the influence of mold weight cannot offset the impact of increased mold weight, resulting in a reverse increase in deformation. For the paving condition, an increase in the number of U and V direction partitions can reduce the deformation of the mold. When the number of U-shaped partitions increases to 6 and the number of V-shaped partitions increases to 3, the deformation decreases and the stiffness stabilizes to the lowest. To verify the accuracy of the optimization results of this structural type, which has achieved a certain degree of improvement in stiffness and

Table 1. System parameter.

No.	Parameter category	Parameter Name	Parameter Value	Remarks
1	Software	Modeling software	SolidWorks 2018	Used for 3D modeling of mold structure
2		finite element Analysis software	ANSYS 19.2	Used for stress and strain analysis of mold structure
3		Optimization software	MATLAB R2018b	Used for parameter optimization
4	Hardware	Computer model	Dell precision 5540	Main frequency 2.6GHz, memory 16G
5		Operating system	Windows 10 professional Edition	64-bit operating system
6		Processor	Intel® core™ i7-9750H	Used for running the above software



(a) Hoisting and transportation conditions (b) Forklift transportation conditions



(c) Paving conditions

Fig. 7. Curved surface diagram of the relationship between the number of U/V direction partitions and deformation under various working conditions.

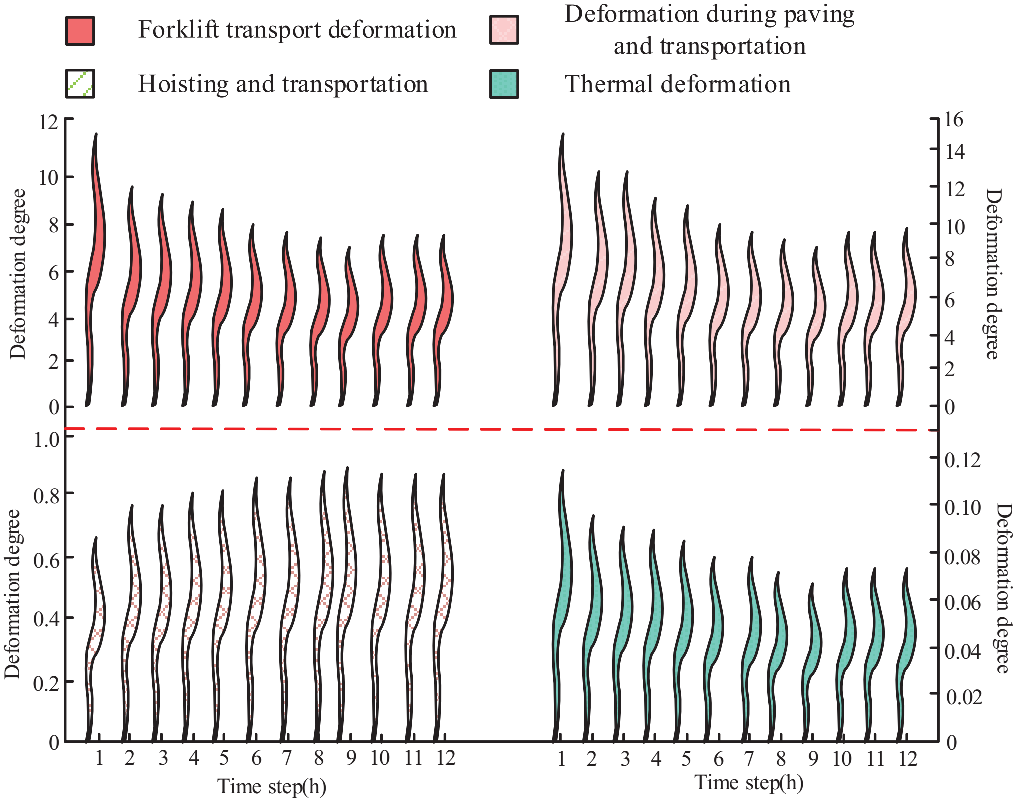


Fig. 8. Deformation of the optimized mold under various working conditions.

strength compared to the original mold structure, FE analysis is used to verify the deformation and temperature field distribution of this structural type under various working conditions. The deformation degree of each working condition of the optimized mold is shown in Figure 8.

In Figure 8, the performance comparison between the original structure and the optimized structure shows that the deformation of the optimized structure is reduced to varying degrees under four operating conditions: forklift transportation, lifting transportation, paving, and hot deformation of the hot pressing tank. Specifically, the deformation during forklift transportation decreased by 36.5%, during lifting transportation decreased by 13.9%, during paving deformation decreased by 36.9%, and during hot pressing, the deformation of the tank decreased by 18.2%. This indicates that the optimization method for mold structure type used and its optimization results are accurate and feasible.

4.2 Comparison of optimized performance of composite material forming molds integrated with response surfaces

After analyzing and verifying the support baffle structure of composite material forming molds, this study further investigates the optimization effect of molds under different parameter combinations. Response surface methodology, as an experimental design and optimization method, can establish mathematical models on the ground of a small number of experiments and find the most advantageous process response values. The fitting curve is shown in Figure 9.

In Figure 9, the points corresponding to mold quality, forklift deformation, lifting deformation, paving deformation, and thermal deformation are very close to the diagonal. This indicates that the set response points and their response values are within a reasonable range, indicating that the fitting accuracy of the model is relatively high. The Pareto optimal solution set graph calculated using NSGA-II is shown in Figure 10.

In Figure 10, the population size of each generation is set to 100, the crossover probability is set to 0.6, and the mutation probability is 0.04. Through 13 iterations, a total of 1200 design points are calculated. After the optimization of the mold, FE verification is carried out, as shown in Figure 11.

In Figure 11, after optimization, the maximum deformation of the mold under forklift transportation, lifting, and paving conditions is similar to or slightly reduced from the original model. Meanwhile, the thermal deformation and mold quality of the mold are reduced by 28% and 12.8%, respectively. The Pareto optimal solution validation obtained by the NSGA-II algorithm shows that the approximate model calculation results are consistent with the actual FE analysis results. The maximum relative error between mass and deformation is 4.7%, and the average error is 3.5%, both within a reasonable range, verifying the reliability of the optimization results.

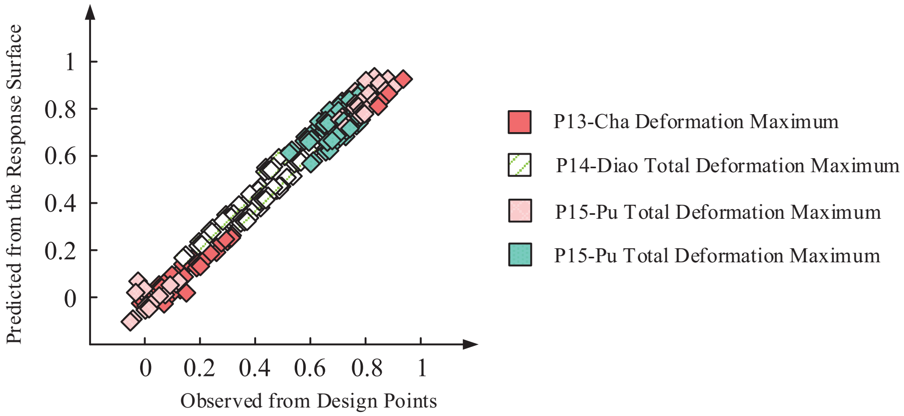


Fig. 9. Fit curve for optimizing performance.

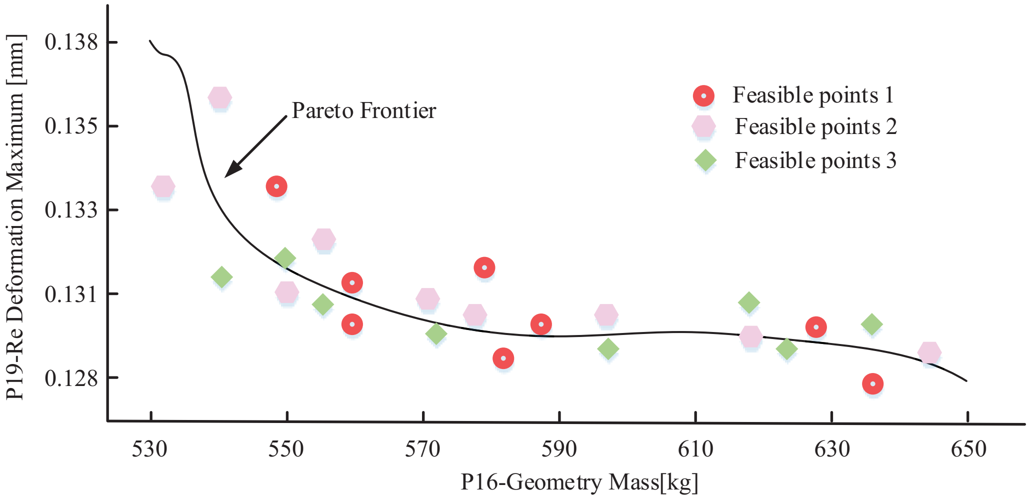
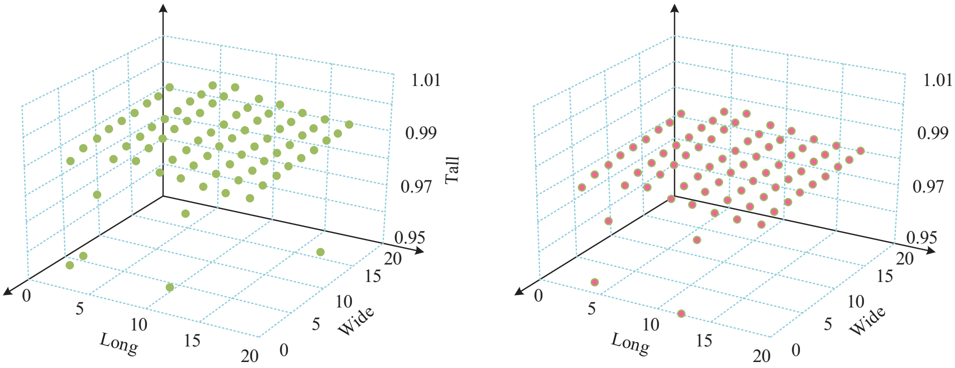


Fig. 10. Pareto optimal solution set graph calculated using NSGA-II.

In addition, the maximum equivalent stress under each working condition is much lower than the yield limit of the material, ensuring that the mold strength meets the design requirements.

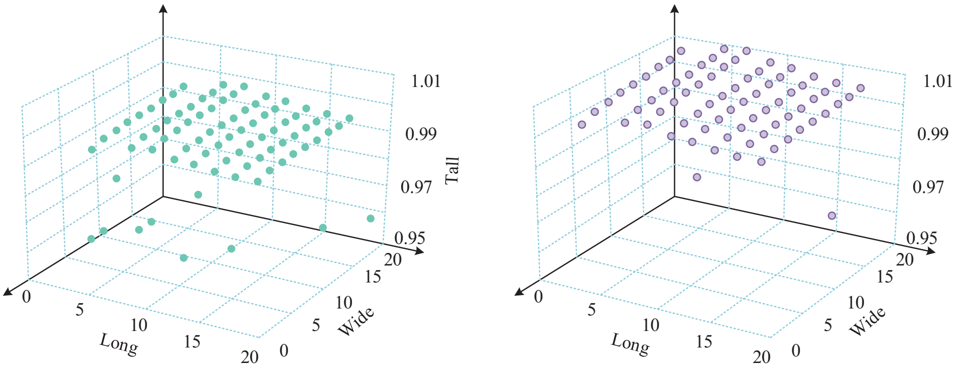
5 Conclusion

In the design of composite material forming molds, the optimization design of the mold support structure partition is a key link, which can significantly improve the performance of the mold, reduce mold deformation, and increase mold stiffness. Response surface methodology was utilized in this study to optimize the design of the mold support structure partition. The objective was to identify a support structure partition design scheme that minimizes mold deformation and maximizes mold stiffness. The experimental results showed that when the number of U-shaped partitions increased to 6 and V-shaped partitions increased to 3, the deformation decreased and the stiffness stabilized to the lowest. To find the optimal solution, the population size of each generation was set to 100, the crossover probability was set to 0.6, and the mutation probability was 0.04. Through 13 iterations, a total of 1200 design points were calculated. The Pareto optimal solution verification showed that the approximate model calculation results are consistent with the actual FE analysis results. The maximum relative error between mass and deformation was 4.7%, and the average error was 3.5%, both within a reasonable range, verifying the reliability of the optimization results. The research results have important reference value for the design of composite material forming molds, helping to improve the performance and efficiency of the molds and reduce costs. However, there are still some shortcomings in the research, such as the lack of in-depth research on the performance of molds under other working conditions. Future work will aim to expand optimization frameworks to encompass a broader range of working conditions and address the dynamic response of molds under different operating stresses. Additionally, investigations will be conducted to assess the long-term durability and wear resistance of optimized molds in industrial environments, ensuring their sustained performance.



(a) Forklift transport deformation

(b) Deformation during lifting and transportation



(c) Forklift transport deformation

(d) Thermal deformation

Fig. 11. Finite element verification after mold optimization.

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Conflict of Interest

The authors declare no conflict of interests.

Data availability statement

All data generated or analysed during this study are included in this published article.

Author contribution statement

The response surface method was used to optimize the design of the mold support structure partition, improving the performance parameters of the mold by increasing the number of U and V direction partitions. C. L. analyzed the data, H. J. and L. Z. helped with the constructive discussion. H. J., Q. L. and J. Q. made great contributions to manuscript preparation. All authors read and approved the final manuscript.

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