Optimization Design Technology for the Framed-mould Bracing Structure Based on Metamodel

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Abstract. Based simulation results, the sensitivities of the mould stiffness and heat transfer design result to the mould structure design parameters were analyzed, and the expressions of relations between maximum temperature difference during warming, maximum temperature difference during cooling, maximum compressive deformation, maximum thermal deformation and design parameters were established through data fitting. Ignoring the insensitive parameters, the Metamodel optimum design model was established for the mould bracing and heat transfer structure, and the rapid optimum design for the mould bracing structure was achieved.

Introduction

Resin Matrix Composite, or RMC for short, with the unique advantages over metal materials in specific strength, stiffness, corrosion resistance, dimensional stability, anti fatigue-fracture property, desirable property and the property of being easily overall molded in large formats, are being widely used in the fields of aviation and astronavigation. Particularly in aviation, most of the existing large aircraft tend to the application of RMC parts. For example, the resin-based composite materials used for Boeing787 amount to 45%, correspondingly reducing the weight by 20% in structure [1-2]. At present, our large aircraft composite parts are also being developed, and large commercial aircrafts made of domestic composite parts are planned to make the first flight in several years. During the course of making large-format RMC parts with the format of 2 to 8 m and thickness of 2 to 20mm, in consideration of their high intensity, forced assembly is forbidden when aircrafts are being assembled. Their shapes which may affect the aerodynamic performance of aircrafts are required to be made in high precision with a small amount of deformation and consistent performance of each part. Autoclave molding technology is the main technology of molding large-format RMC parts of complex shapes, which, compared with other molding technology, has the advantages of making parts of higher performance and more stable quality[3].

During the course of autoclave molding RMC, apart from providing the prepreg with suitable molded surface to accurate its shape after curing, the main function of the mould also includes guaranteeing the mould surface in small temperature difference and deformation. As the temperature difference of the mould surface may cause unsynchronization in parts curing, which may cause excessive internal stress in the parts and accordingly affect their quality. Besides, molded surface deformation may cause parts deformation, thus increasing the size deviation in molding. Therefore, a rational design of mold heat transfer structure and the support structure is required to balance the stiffness and heat of the mould. The frame mould required in autoclave molding method which directly affects the size, shape accuracy and internal quality of the parts, is one of the key equipment in manufacturing large-format RMC parts.
Optimization Design of Mould Frame Based on Metamodel

Mould work control parameters refers to the control range of the temperature change and structure deformation of the molded surface to ensure the quality of the parts in the process of autoclave molding. Based on the results of the mould heat transfer simulation, this section is focused on optimizing the mould structure design parameters, aiming to minimize the overall mass of the mould. As the size of the moulded surface is quite large, at heating and cooling stage of the autoclave, temperature gradient can be produced in different positions of molded surface. At the heating stage, the temperature around the molded surface is higher than that of the center of the surface; at the cooling stage, the temperature of the center of the molded surface is higher than that around the surface. When the temperature difference in the temperature field increases to the maximum, the heating stage of the autoclave ends. Temperature difference may cause deformation of the molded surface, so it must be controlled in a certain range. Besides, structure deformation of the mould is caused by two factors. One is stiffness controlling parameters of the mould, referring to the elastic deformation of the mould caused by compressing the mould structure. The other is the structural deformation caused by thermal expansion of temperature of the mould. In the process of parts curing, elastic deformation of the mould may be caused under the joint action of air pressure in the autoclave and vacuum pressure in the vacuum bag, and it may be passed to the parts being molded, which may increase parts deformation. The elastic deformation of the mould is mainly related to its stiffness, so a scientific and rational design of mold structure is required in mould designing. Combined with the previous designing experience, the following four controlling parameters are the constraint conditions which must be met in mould designing:

A framed-mould of large-format parts could be ten or more meters in length and several meters in width, and its size and quality greatly impact the cost of the mould. A good mould should be as light as possible on the basis of satisfying the above constraints. So the aim of optimizing the mould design is to try to use less material on the basis of satisfying the constraints.

The optimization technology based on Metamodel consists of three parts: experimental design, structure of Metamodel, optimization base on Metamodel[4].

In the previous section, optimized parameters are selected through the single factor and multi level change test. This section is targeted at setting up a function relation between mould optimization objective and constraint conditions and establishing Metamodel applied in optimizing calculation.

The uniform experimental design is adopted to take the value evenly in the range of every parameter so as to get the virtual experiment result.

1. Fit the temperature difference at heating stage by multiple linear fitting, shown in Eq.1:

\[
\Delta T_{heating} = 8.59048 + 1.48289 \cdot x_4 \cdot x_5 - 5.69451 \cdot 10^{-2} \cdot x_1 \cdot x_6 + 1.06748 \cdot 10^0 \cdot x_1 \cdot x_7 - 1.73839 \cdot x_1 \cdot x_7 - 3.56028 \cdot 10^{-3} \cdot x_4 \cdot x_6 + 3.75319 \cdot 10^{-4} \cdot x_1 \cdot x_5 - 7.04573 \cdot 10^{-2} \cdot x_5 \cdot x_6 - 9.40989 \cdot 10^{-3} \cdot x_5 \cdot x_6 - 1.78835 \cdot x_5 \cdot x_6
\]  

\( x_1 \) as length of the mould (mm); \( x_2 \) as width of the mould(mm); \( x_3 \) as vent opening ratio; \( x_4 \) as the thickness of molded surface (mm); \( x_5 \) as wind speed (m/s); \( x_6 \) as pressure (atm) \( x_7 \) as heating rate (K/min).

2. Get the temperature difference of the molded surface at the cooling stage by the same method through uniform experimental design shown in Eq.2:

\[
\Delta T_{cooling} = -3.60479 + 1.26892 \cdot x_4 \cdot x_7 + 1.29902 \cdot 10^{-1} \cdot x_5 \cdot x_6 - 6.53009 \cdot 10^{-2} \cdot x_4 \cdot x_5 - 4.48388 \cdot 10^{-1} \cdot x_4 \cdot x_5 + 1.80606 \cdot 10^{-3} \cdot x_5 \cdot x_6 + 1.15046 \cdot x_4 \cdot x_7 - 7.14161 \cdot 10^{-1} \cdot x_5 \cdot x_6 - 3.60786 \cdot 10^{-3} \cdot x_5 \cdot x_6 - 9.44961 \cdot 10^{-1} \cdot x_7 \cdot x_7
\]  

(2)

3. Get the maximum deformation of the molded surface at the heating stage by the same method through uniform experimental design shown in Eq.3.
\[
\delta_{\text{heating}} = \delta_0 + \delta_{x_1} + \delta_{x_2} + \delta_{x_3} + \delta_{x_4} + \delta_{x_5} + \delta_{x_6} + \delta_{x_7} \\
\delta_0 = 0.38047 \\
\delta_{x_1} = 0.00000733476x_1 + 0.00006892x_1 - 0.26436 \\
\delta_{x_2} = 0.00000012245x_2^2 + 0.00006629x_2 - 0.0948 \\
\delta_{x_3} = 0.24027e^{\frac{x_3}{0.00738}} - 0.00544 \\
\delta_{x_4} = -0.76697e^{\frac{x_4}{2.58318}} - 1.36858e^{\frac{x_4}{2.00935}} + 0.64288 \\
\delta_{x_5} = 3.16025e^{\frac{x_5}{0.23316}} - 0.00008 \\
\delta_{x_6} = -1.1851e^{\frac{x_6}{4.3200}} + 0.83745 \\
\delta_{x_7} = -1.2384e^{\frac{x_7}{4.3200}} + 0.89235 \\
\]

(4) Get the maximum deformation of the molded surface at the cooling stage by the same method through uniform experimental design shown in Eq.4.

\[
\delta_{\text{cooling}} = \delta_0 + \delta_{x_1} + \delta_{x_2} + \delta_{x_3} + \delta_{x_4} + \delta_{x_5} + \delta_{x_6} + \delta_{x_7} \\
\delta_0 = 0.38047 \\
\delta_{x_1} = 0.00000733476x_1 + 0.00006892x_1 - 0.26436 \\
\delta_{x_2} = 0.00000012245x_2^2 + 0.00006629x_2 - 0.0948 \\
\delta_{x_3} = -1.23852e^{\frac{x_3}{4.3200}} + 0.89235 \\
\delta_{x_4} = -0.76697e^{\frac{x_4}{2.58318}} - 1.36858e^{\frac{x_4}{2.00935}} + 0.64288 \\
\delta_{x_5} = 3.16025e^{\frac{x_5}{0.23316}} - 0.00008 \\
\delta_{x_6} = -1.1851e^{\frac{x_6}{4.3200}} + 0.83745 \\
\delta_{x_7} = -2.47148e^{\frac{x_7}{4.3136}} + 1.91692 \\
\]

(5) Mass of the mould. Select the mass of the mould at the thickness ratio of 1:1.75 between supporting frame plate and molded surface, shown in Eq.5.

\[
G_{mould} = x_1x_2x_4 + 0.7(1-x_3)x_4h_{frame}x_4n_{hole-length} + 0.7(1-x_3)x_2h_{frame}x_4n_{hole-width} \\
x_1 \text{ as length of the mould (mm); } x_2 \text{ as width of the mould(mm); } x_3 \text{ as vent opening ratio; } x_4 \text{ as the thickness of molded surface (mm); } h_{frame} \text{ as the height of the mould (mm); } n_{hole-length} \text{ as the number of supporting frame in the flow direction of the mould; } n_{hole-width} \text{ as the number of supporting frame in the radial direction of the mould.}
\]

Among the seven factors affecting the temperature difference and deformation of the molded surface, mould length, mould width, mould thickness and opening ratio are of the structure designing factors. Opening ratio is the optimized parameter acquired by simplifying the parameters of the shape and size of the side wall of the vent. Mould length and width are determined by the size of the molded parts, so they cannot serve as the optimized parameters. Process parameters like wind speed, pressure, heating rate and cooling rate in the autoclave are determined by the molded material, so neither can they serve as the optimized parameters. The temperature difference of the molded surface at the heating and cooling stage is affected by mould design and process parameters.

Mould length \(x_1\) and mould width \(x_2\) in Eq.1 and Eq.2 are determined by the system based on the size of the parts and empirical formula, and these parameters will be assigned a value before performing the optimization design. As for wind speed \(x_3\), pressure \(x_6\), heating rate or cooling rate \(x_7\) among the process parameters, they are determined by this resin process database and will be assigned a value before performing the optimization design.

By simplifying the parameters, the major optimized parameters of the mould structure optimization design are vent opening ratio \(x_3\) and thickness of molded surface \(x_4\), and the process of
Optimization can be described as the minimization problem of constrained nonlinear function, shown in Eq.5.

**Optimized objective:**

- Constraint condition of temperature difference of molded surface at the heating stage
- Constraint condition of temperature difference of molded surface at the cooling stage
- Constraint condition of deformation of molded surface at the heating stage
- Constraint condition of deformation of molded surface at the cooling stage

**Parameter range:**

- Parameter range: $0 < \text{vent opening ratio } x_3 < \text{allowable maximum opening rate}$
- $0 < \text{thickness of molded surface } x_4 < \text{allowable maximum thickness of mould wall thickness}$

Solve the optimized model with finicon, the nonlinear equality and inequality optimization problem function in optimization design module of Matlab and define the mold constraint condition with function noncon so as to solve the nonlinear constraint of this model. Furthermore, develop this process as a MMC file, call it with VC programming to get the results of mould supporting structure optimization.

### Application Example

Optimize the supporting structure and heat transfer structure in the initial mould design.

- Basic mould size: 1700mm in length, 1200mm in width and 400mm in height with 8 vents in the flow direction and 6 vents in the radial direction.
- Process parameters: heating rate 1.5K/min, cooling rate 1.5K/min, pressure in the autoclave: 1 atm

Optimized objective: (opening ratio $x_3$, thickness of molded surface $x_4$)

- Constraint condition of temperature difference of molded surface at the heating stage
- Constraint condition of temperature difference of molded surface at the cooling stage
- Constraint condition of deformation of molded surface at the heating stage
- Constraint condition of deformation of molded surface at the cooling stage

**Parameter range:**

- Parameter range: $0 < \text{vent opening ratio } x_3 < 0.6$
- $0 < \text{thickness of molded surface } x_4 < 50$

Optimization results: Opening ratio $x_3=0.3775$, thickness of molded surface wall $x_4=3.7429$mm

Steel plate thickness rounded according to national standard thickness series: $x_4=4$mm, thickness of the supporting plate taken as 3mm by approximately 0.7 times of the thickness of the molded surface.

- Total area of the vent in flow direction: $1700 \times 400 \times 0.3775 = 256700 \text{mm}^2$, each sectional area of eight evenly distributed vents: $32087 \text{mm}^2$, if height is taken as 300mm, width will be 107mm
- Total area of the vent in radial direction: $1200 \times 400 \times 0.3775 = 181200 \text{mm}^2$, each sectional area of six evenly distributed vents: $30200 \text{mm}^2$, if height is taken as 300mm, width will be 100mm

Total mass of the mould: $G_{mould}=176.748$kg

Mould design result are shown in Figure 1

![Figure 1. The mould design result after optimization procedure.](image)

After optimization procedure:

Total mass of the mould before optimization is 194.723kg and 176.748kg after optimization, losing 9.23% of the mass during the procedure. After optimization, the maximum temperature difference of the molded surface is 14.4°, deformation of the molded surface is 1.9278mm, which meet the
design requirements. At the end of heating after the optimization, the temperature distribution at the moment of the maximum temperature difference is shown in Figure 2 and the deformation distribution of the mould is shown in Figure 3, also meeting the design requirements.

![Figure 2. Temperature distribution of the optimized mould at t=17500s.](image1)

![Figure 3. Deformation of the optimized mould at t=17500.](image2)

**Conclusion**

In this paper, a heat transfer simulation model of the framed mould working in the autoclave is firstly established, and the simulation of this process is realized by using ANSYS-CFX system. Secondly, a simulation model of mould deformation process caused by thermal expansion and compression when the framed mould is working is established, and a mould deformation is simulated on the basis of the heat transfer simulation by using ANSYS-CFX system. By comparing the simulation results with experimental results, this simulation method is proved to be of high simulation accuracy. Then by using this simulation tool, a rule of how the mould structure design parameters and the process parameters affect the temperature difference and deformation of the molded surface is analyzed, and the sensitive level of each parameter to the temperature difference and deformation of molded surface is also analyzed, by which a conclusion that the thickness of the molded surface and the opening ratio of the supporting frame is the sensitive parameters that affect the design result is drawn. Finally, the uniform experimental method is adopted to establish the relationship among each design parameters, optimized objective and constraint condition. In this section, insensitive parameters are ignored and Metamodel calculation model used to optimize mould supporting structure is established. Besides, an application example is set to prove that this model can get quite good optimization design results on the basis of guaranteeing the constraint conditions and mostly importantly, it can reduce the long calculation time and improve the efficiency of the optimization design.

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