Research on cooling channel design of aluminum alloy die-casting mould based on simulation and topology optimization

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Abstract: In the process of aluminum alloy die casting, there is often a problem of temperature imbalance in the process of mold filling and solidification. The cooling system controls the solidification rate of the casting by providing cooling medium, and by optimizing the layout and flow path of the cooling system, the temperature imbalance in the cooling process can be reduced and the production efficiency can be improved. Topology optimization is an optimization method applied in engineering design, which aims to achieve lightweight and performance improvement of structures by adjusting the topology shape of structures. In this paper, the design of die cooling channel for aluminum alloy bottom die-casting based on moving morphable components (MMC) method is studied. Firstly, the structure and forming characteristics of aluminum alloy bottom die casting were analyzed, and the filling solidification process was simulated. Secondly, according to the simulation results, the solidification heat transfer law is summarized, and the high temperature area in the process of die casting is obtained. Thirdly, an automatic design model of cooling system based on MMC method is established based on the obtained hot zone of die casting process. Finally, the topology optimization results are compared with the hot zone of die casting, which proves the effectiveness of the model and the rationality of the designed cooling system.

Keywords: Aluminum alloy; Die casting; Cooling channel; Topology optimization

1 Introduction

With the development of complex and lightweight structural parts in the fields of new energy vehicles, aerospace and high-end equipment, the casting and forming of lightweight metal structural materials is facing greater technical challenges. Aluminum is a lightweight, high-strength, corrosion-resistant light alloy, which is widely used in aerospace fields such as aircraft fuselage, engine parts, satellite structures, and automotive manufacturing fields such as body, engine, and chassis. Due to the demand of lightweight and high performance, aluminum alloy castings are developing towards large complex thin-wall. For example, integrated die-casting aluminum alloy castings have large size and complex process, which also has higher requirements for the complexity of aluminum alloy structure materials, and its casting is also facing more severe technical challenges. Therefore, such large and complex thin-walled aluminum alloy components put forward higher requirements for the cooling system design and process parameter selection of the die.

In the process of aluminum alloy die casting, there is often a temperature imbalance problem in the filling and solidification process. The cooling system controls the solidification rate of the casting by providing a cooling medium. Appropriate cooling can ensure that castings contract uniformly during the solidification process, avoiding defects such as Shrinkage Cavity and cracks. Therefore, the design of cooling system directly affects the quality and production efficiency of castings, and its importance can not be ignored. A reasonable cooling system can speed up the solidification rate of castings, thereby shortening the production cycle. At the same time, by optimizing the layout and flow path of the cooling system, the cooling effect can be improved, the cooling time can be reduced, and the production efficiency can be improved.

Numerous studies have been conducted on simulation and automatic design of cooling channels for die casting at home and abroad. Behrens et al.[1] conducted a numerical simulation study on a hot forging die with an internal cooling channel. The stress state under different process conditions was explored. Federica et al.[2] studied two alternative cooling systems of a mold insert used in die casting process of light alloy components. Chavan et al.[3] designed and optimized the cooling channel position for cold chamber high pressure die casting machine. Pelaccia et al.[4] studied the efficiency of conformal cooling channels inserts for extrusion Dies. Yavuz et al.[5] analyzed the cooling system performance in aluminum low pressure casting using numerical simulation. Kurtulus et al.[6] conducted an experiment to study the cooling and heating performance of a gravity die casting mold with conformal cooling channels.Lei Shu et al.[7] designed the conformal cooling for a die-casting mold insert. Dhisale et al.[8] reduced the shrinkage porosity of the aluminum alloy wheels by optimizing the parameters of the cooling channels in the low-pressure die-casting process. Arunkumar et al.[9] studied the flow and heat transfer law of die casting cooling channel under high pressure.

Moving morphable components (MMC) method is one of the essential topology optimization methods. It is proposed by Guo Xu[10-14]. This method has fewer design variables and lower grid dependence compared with the variable density method. Furthermore, it support to display topology changes[15]. Takalloozadeh et al.[16] used topology derivative to enhance the effect of MMC method. Rixin Wang et al.[17] controlled the minimum length scale in MMC method based on effective connection method. MMC method is also fit for different structures, including thin plate[18], composite stiffened panel[19], and hollow structure [20]. Some new techniques, including projection transformation[21] and deep learning[22], are also well integrated with MMC. This shows the great development potential and wide applicability of MMC method.

In this work, the cooling channel design of aluminum alloy bottom die casting based on MMC method is studied. Firstly, the structure and forming characteristics of aluminum alloy bottom die casting were analyzed, and the filling and solidification process was simulated. Secondly, according to the simulation results, the solidification heat transfer law is summarized, and the area of high temperature in the die casting process is obtained. Thirdly, based on the obtained overheating area of die casting process, an automatic design model of cooling system based on MMC method was established. Finally, the effectiveness of the model and the rationality of the designed cooling system were proved by comparing the topology optimization results with the overheating area of die casting.

2 Structural analysis and simulation

The casting studied in this paper is the aluminum alloy bottom shell die casting used in an automobile, and the 3D model of the casting is shown in Fig 1. It can be seen from the figure that the overall size of the casting is large, especially in the direction of length and width, which makes the overall filling process relatively long. The wall thickness of the casting is extremely thin, the thinest wall thickness is 2.8 mm. Therefore, if the injection speed is low or the temperature is unbalanced, it is easy to cause defects such as cold isolation. There are a large number of positioning holes and other components inside the shell casting, and the processing has high requirements for its dimensional accuracy. If the local overheating causes thermal deformation in the die-casting process, the size will change greatly and affect the later assembly. According to the above structural characteristics, the casting and arranging system of aluminum alloy bottom shell die casting is designed, as shown in Fig 2, which can minimize the filling process and achieve simultaneous solidification. The overflow groove is designed for the last filling area in the casting and the thick and prone to porosity parts, which can minimize Shrinkage Cavity and porosity to the greatest extent.

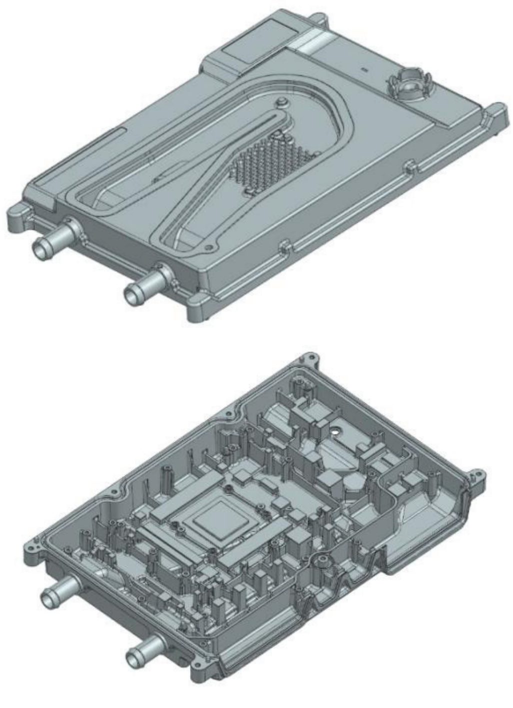

Fig 1 3D model of aluminum alloy bottom shell casting

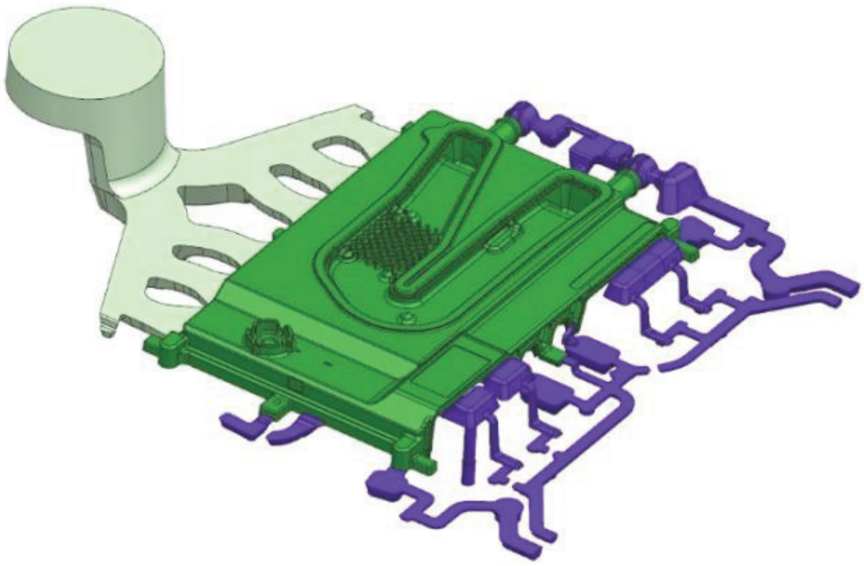

Fig 2 3D model of pouring and riser system for the bottom shell die casting

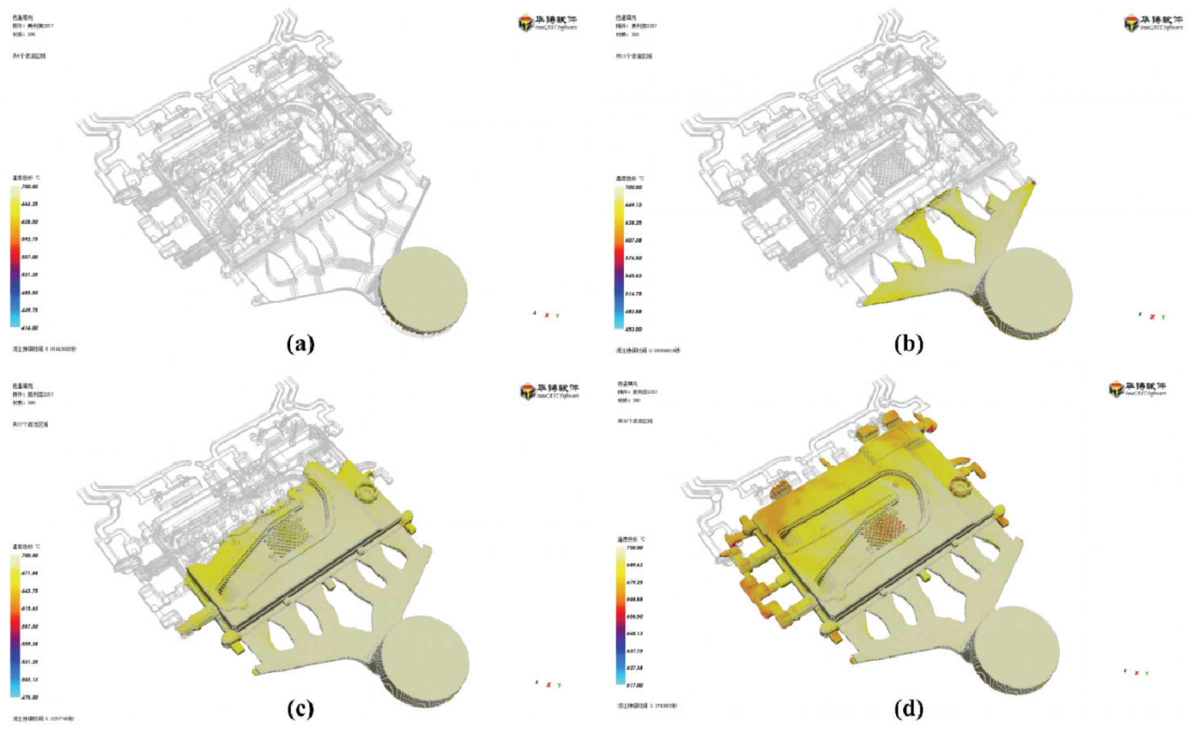

Fig 3 Coupling simulation results of mold filling and heat transfer in bottom shell casting

The filling flow process of this casting was simulated, and the coupling simulation results of filling and heat transfer were obtained, as shown in Fig 3. It can be seen from the figure that there is a large difference in the filling process between different positions of the casting, the furthest filling process is longer, and the overall temperature of the casting near the runner side is higher, and the temperature far away from the runner side is lower, which is very likely to lead to temperature imbalance of the casting and lead to deformation and other defects. In addition, it can be seen from Fig 3 (d) that there is overheating in some thick areas on the top of the casting. Therefore, it is necessary to design a targeted cooling system to optimize the filling and solidification process.

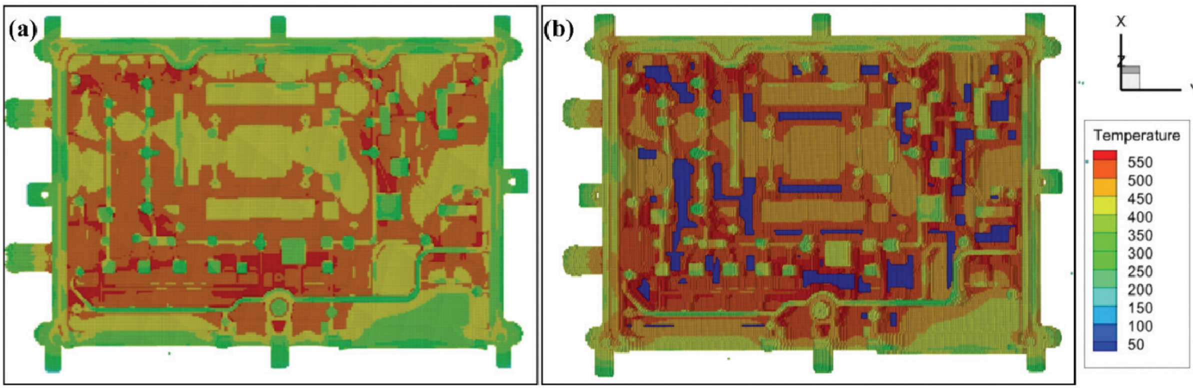

Fig 4 Temperature field and superheated area of the bottom shell during die casting

By analyzing the filling and solidification simulation results of the casting, the overheated area of the bottom shell casting in the die-casting process was obtained, as shown in Fig 4. Fig 4 (a) is the temperature field distribution result, and the blue part in Fig 4 (b) is the overheated area in the die-casting process obtained by the algorithm. As can be seen from the figure, the overheated areas are mostly concentrated at the connection points of the support plates inside the bottom shell and the local thick areas. These areas often solidify last during the forming process, which not only leads to Shrinkage Cavity and porosity. Moreover, the overall deformation of the casting will be caused by the heat action, or the residual stress will be generated inside the connection, thus affecting the quality of the casting. Therefore, for this type of area, the cooling system should be used to take away part of the heat to realize the simultaneous solidification of each part of the casting.

3 Cooling channel design based on topology optimization

Based on the temperature overheating results obtained by the above simulation, the cooling runner design based on topology optimization is carried out. Firstly, we need to simplify the physics. In order to ensure the accuracy and efficiency of the model, the physical process involved is simplified as follows:

(1) Since the casting has a large size in the direction of length and width, and a small size in the direction of height, only the cooling flow channel design in the two-dimensional plane is considered when designing the cooling flow channel.

(2) When defining the design space, only the overheating region obtained above is considered, and the temperature field of the rest part is ignored. Therefore, the whole design space is divided into two parts, namely the overheating region and the non-overheating region.

(3) Considering the practical application requirements and in order to make the model run efficiently, only horizontal and vertical cooling channels are considered in the design of cooling channels.

(4) The model does not consider the design of point cooling system, only consider the design of shape cooling channel.

(5) The model does not consider other variables such as flow rate and cooling medium, and only considers the structural design of the cooling channel.

After the model simplification and assumptions are completed, the topology optimization design of the cooling flow channel is carried out based on the MMC method. In MMC method, the geometric structure is described as a number of components that can move and deform. These components change the topology of the structure by constantly moving, deforming, intersecting and covering, and these changes are evaluated by a specific objective function. In the framework of MMC topology optimization, each component can be described by only a few parameters. Compared with the methods such as variable density method that rely on changing pixels for optimization, the design variables are greatly reduced, so it is more efficient.

In this model, in order to apply the movable deformation components, the overall cooling channel to be designed is divided into multiple components, and each component is connected after the topology optimization, and the purpose of the design is achieved. Therefore, the overall design is divided into three steps, (1) The MMC-based topology optimization method is used to design multiple components. 2.Filter the resulting components. (3) Connect the selected components to obtain the final cooling channel design scheme. The schematic diagram of its process is shown in Fig 5.

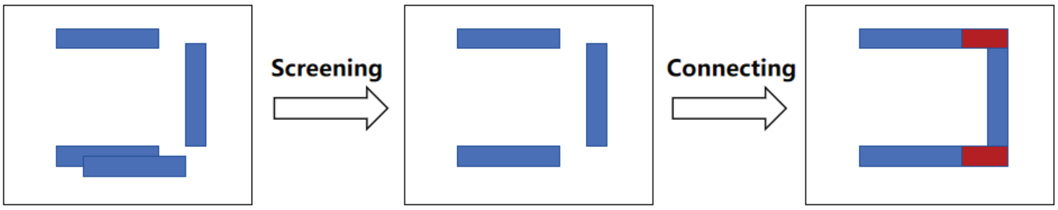

Fig 5 Design process of cooling channel

Firstly, MMC-based topology optimization methods are required to design for multiple components. In order to ensure that the cooling channel can well cool the overheating area, it is necessary to make the designed cooling channel as close as possible to the overheating area, and to use the cooling channel as little as possible in the part without overheating area. In addition, it is necessary to make the number of cooling channels as small as possible on the basis of ensuring the cooling effect. If the area where the cooling flow channel is S_1, the area where the overheating area is S_2, and the area where the two parts intersect are defined is S_3, the design goal of the model is as follows:

$$\begin{cases} \max S_3 \\ \min S_2 - S_3 \\ \min S_1 \end{cases} \tag{1}$$

After the definition of model design variables, design goals and so on, the components in this model are described by topological description functions. Since the components in this model are two-dimensional components, for a conventional two-dimensional component, its topological description function can be described by the following governing equation:

$$\chi(x,y) = 1 - \left(\frac{x'}{L}\right)^p - \left(\frac{y'}{f(x')}\right)^p \tag{2}$$

where:

$$\begin{Bmatrix} x' \\ y' \end{Bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{Bmatrix} x - x_0 \\ y - y_0 \end{Bmatrix} \tag{3}$$

This function can be used to describe common 2D components, and the topological description function of a typical 2D component is shown in Fig 6.

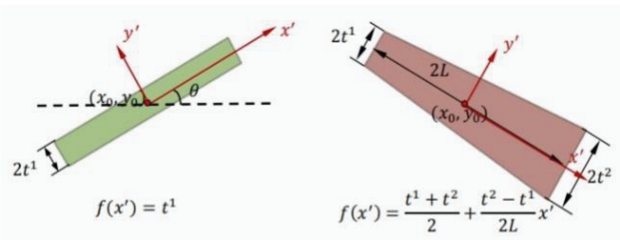

Fig 6 Topological description functions for typical 2D components

In this model, we simplify each component into a two-dimensional cuboid, so the only variables that can be changed are position, length L, width d, and direction Angle θ. The design variables are:

$$D = (x_0, y_0, L, d, \theta)^T \tag{4}$$

In these variables, the range of x_0 and y_0 is the design space of the cooling channel. Considering that the width of the pipeline should be the same in the design process of the cooling channel, the value of d is fixed and the value of L is free.

After describing the topology of a single component, this description method is extended to multiple components. At the beginning of the model, the control parameters of multiple components are randomly generated, and each control parameter is changed and optimized in each iteration step. When optimizing the control parameters, the moving asymptote method [16] is used for optimization. The Moving Asymptotes Method is a numerical method for solving nonlinear optimization problems. It approaches the optimal solution gradually by introducing an asymptote to approximate the objective function and updating the position and slope of the asymptote in each iteration. The basic idea of this method is to transform the objective function into an equivalent constraint problem, and to approximate the constraints by introducing asymptotes. The steps are as follows:

(1) Initialization: Choose an initial point as the starting point of the search, and set the position and slope of the initial asymptote.

(2) Update the asymptote: Update the position and slope of the asymptote based on the position of the current point and the gradient of the objective function.

(3) Solve the subproblem: Compare the objective function to the asymptote to get a subproblem. A new search direction can be obtained by solving this subproblem.

(4) Update the searching point: Update the position of the current point according to the search direction and step size.

(5) Determine the termination condition: According to

the preset termination condition, determine whether the optimal solution is reached or the optimization cannot continue.

6.Iterative update: If the termination criterion is not reached, go back to step 2 and continue to iteratively update the asymptotics and search points.

The advantage of the moving asymptote method is that it can handle nonlinear constraints and non-convex problems, and it converges faster. However, this method also has some drawbacks, such as being sensitive to the choice of the initial point, and may fall into a local optimal solution. When using this method, it is important to choose the initialization parameters. In order to prevent falling into the local optimal solution, on the basis of using the moving asymptote method, a greedy algorithm is introduced to effectively balance the depth-first and breadth-first search strategies.

After the optimization of the control parameters of the components, the components need to be screened. The reason for this is that we need to limit the number of components when concatenating multiple optimized components. When filtering components, we need to define filtering principles. The basic filtering principles are as follows:

(1) If two components overlap or are too close to each other, keep the one with a higher coverage degree with the superheated area.

(2) Remove components that have low coverage of the superhot region.

Finally, the components after screening are obtained, and these components are connected to complete the design of cooling channels. When connecting, the design goal is to make the cooling channel area outside the superheated zone as small as possible, so it is necessary to ensure that the path used to connect the components is as short as possible. The specific implementation method is to start from a certain component, traverse to search its nearest component end, and connect, and then establish a disabled library, write the two connected ends into the disabled library, the next connection can be searched for the nearest path outside the component, and iterate in turn, and finally all components can be connected. To obtain the final cooling channel design.

3 Model verification and discussion

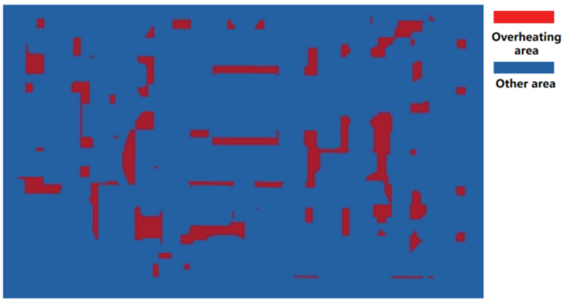

Fig 7 Zoning of the design space

To validate the model, an aluminum alloy bottom die cast was used to design the cooling channel. Firstly, the design space needs to be initialized. According to the initialization process described above, the design space is divided into overheating area and non-overheating area, as shown in Fig 7. As can be seen in the right figure, the distribution of the overheated region is relatively scattered, therefore, when performing topology optimization, it should focus on its breadth-first search.

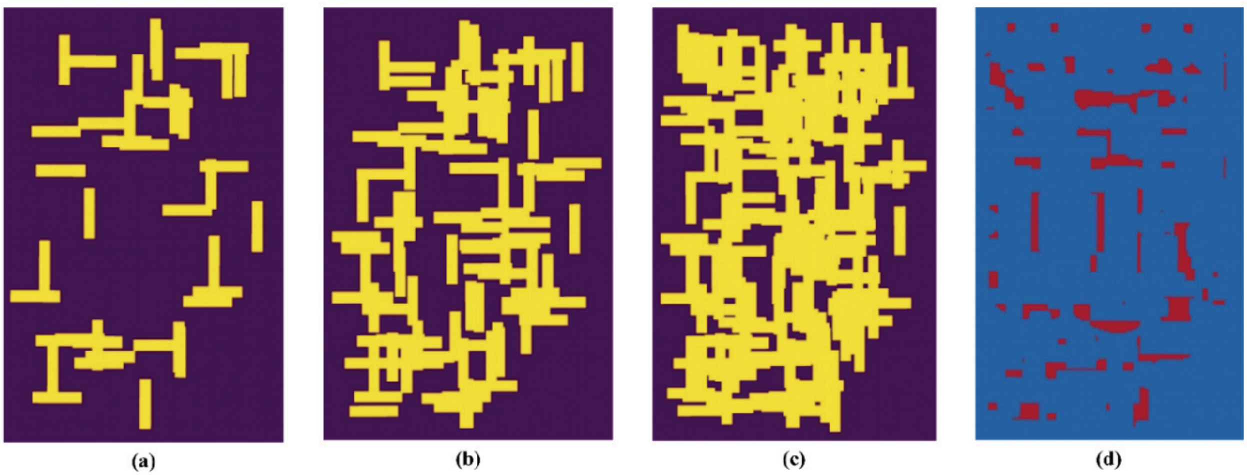

Fig 8 The comparison between the designed components and the overheating area are plotted: (a) 40 components, (b) 100 components, (c)200 components, and (d) distribution of the overheating area

By using the defined design space, the topology optimization based on the MMC method is carried out, and through several iterations, the optimization results shown in Fig 8 are obtained, and it can be seen that the optimized component distribution locations are in good agreement with the overheating region. We obtained several optimization results by setting the number of components. The results with a large number of components can better cover the overheating area, but will also envelope a certain area of the non-overheating area. The optimization results with a small number of components can accurately find the most concentrated part of the overheating area, but will ignore a part of the small overheating area.

the results of 100 components are selected as the design of the cooling channel. After determining the component scheme, the components are screened, and the selected components are connected to obtain the design results as shown in Fig 9. It can be seen from the figure that most of the overheating area is covered by the cooling channel, and the design of the cooling channel conforms to the technological principles. Therefore, the model is effective for the design of the cooling channel.

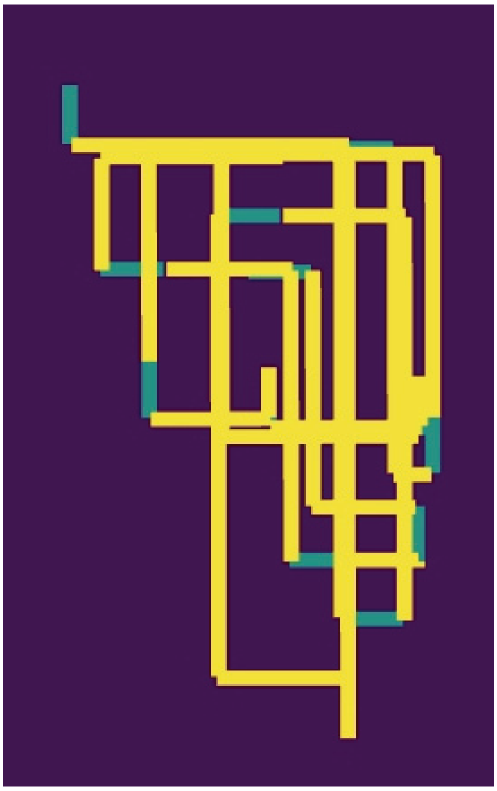

Fig 9 Final design result after connecting components

4 Conclusions

In order to realize the cooling channel design of aluminum alloy bottom die-casting die based on topology optimization, this paper carried out the research of cooling channel design of aluminum alloy bottom die-casting die based on MMC method. The specific summary is as follows:

(1) The structure and forming characteristics of aluminum alloy bottom die casting are analyzed, the casting and discharging system of bottom die casting is designed, and the filling and solidification process is simulated. The simulation results show that the temperature imbalance exists in the solidification heat transfer process of the casting, and the corresponding cooling channel needs to be designed.

(2) According to the simulation results, the solidification heat transfer law is summarized, and the area with excessive temperature in the die casting process is obtained, which provides a design space for the following topology optimization.

(3) Based on the obtained overheating area of die casting process, an automatic design model of cooling system based on MMC topology optimization method is established. Finally, the effectiveness of the model and the rationality of the designed cooling system are proved by comparing the topology optimization results with the overheating area of die casting.

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