Simulation and optimization of casting process for aluminum alloy special-shaped parts

CHEN Min¹, WANG Yi², ZHANG Jigui¹, FU Jiang¹, MA Jianjun*¹

¹ Applied Technology Research Institute, Guizhou City Vocational College, Guiyang, Guizhou, 550025, China
² School of Physics and Electronic Science, Guizhou Normal University, Guiyang, Guizhou, 550025, China

*Professor MA Jianjun is the corresponding author.
E-mail: 624261835@qq.com

Abstract: This article is aimed at an aluminum alloy special-shaped part, which has a hollow connection inside, and there are multiple cross-sections that are constantly changing, and it is difficult to design the casting process. In response to this difficulty, combined with the existing sand casting, metal casting and investment casting production lines of the factory, the casting process plan is designed and optimized now. With the help of the numerical simulation software Anycasting, through the simulation analysis of the casting process, the problem that the castings are prone to defects in the thin wall and the bottom plate is solved. The conclusions obtained from the simulation analysis were applied to the actual production process, and qualified castings were produced.

1. Introduction
Each casting process has its own unique characteristics and advantages, but also has its own different defects and drawbacks [1]. How to combine the advantages of various casting processes, solve the problems in production, and produce more high-quality castings is a problem worthy to study. With the development of rapid prototyping technology, its application in casting production has gradually become popular. Therefore, this article proposes a method of combining 3D printing with traditional metal molds to produce complex aluminum alloy castings, and design the casting process of the castings. At the same time, the corresponding parameters are obtained through numerical simulation to achieve the goal of producing qualified castings.

2. Casting structure
The casting material grade is ZL101A, the outline size is 225×192×90mm, it is a small and medium-sized piece, and the wall thickness is 5-20mm. The shape of the parts is irregular, with a hollow structure in the middle, which is connected by ribs of a special-shaped hollow structure, resulting in hot spots at the corners and cold insulation at the thin wall in the middle. At the same time, the casting has multiple cavities and the cross-section is constantly changing, which makes it difficult to shape the sand core. The three-dimensional drawing of the casting is shown in Figure 1.
3. Casting process design

3.1. Casting process design
The internal structure of the casting is complicated, and the traditional core-making method is used to divide the sand mold into many small pieces to complete, and the sand core is difficult to locate and fix, and it cannot meet the requirements in terms of strength. Now the factory is equipped with three production lines of metal gravity manufacturing, sand casting, investment casting and 3D printing molding equipment. According to the actual situation of the factory, from the aspects of ensuring the quality of the castings and saving economic costs, the combination of external metal gravity casting and internal 3D printing sand cores is used to produce the castings.

3.2. Selection of pouring position
According to the structural shape of the part, the two pouring positions of the part are shown in Figure 2.

Figure 2 Schematic diagram of casting pouring position

Figure 2a shows the pouring position 1 with the large plane facing up to ensure the quality of the lower profiled plate surface and the thin-walled ring. The lower riser of this pouring position is convenient to set up, and it can also provide good feeding for the lower metal. The disadvantage is that the riser part needs to be removed after the pouring is completed, and there are many parts that need to be processed later. The stress is relatively concentrated and easy to break. Figure 2b shows pouring position 2, with the large surface of the casting facing down to ensure the quality of the large surface. Under this pouring position, the pouring system of the casting is easy to design, the sand core is fixed and positioned better, and the riser removal is more convenient. The disadvantage is that the feeder capacity of the riser may not be enough. After comparative analysis, choose the pouring position shown in Figure 2b.

3.3. Determination of Parting Surface
In order to ensure the quality of castings and simplify the casting process, combined with the characteristics of the castings, double parting surfaces are selected, which are located at the largest horizontal and vertical interfaces, and the parting surfaces are flat. This parting method can simplify the design and manufacture of the modelling and template structure, help ensure the dimensional accuracy of the castings, and facilitate core lowering and box closing.
3.4. Design of running and feeding system

Aluminum alloy casting is very easy to oxidize and absorb gas, produce non-metallic inclusions, and the inclusions are difficult to float up and removed, the cooling speed is fast, and defects such as insufficient pouring and cold insulation are easy to occur. The volume shrinkage rate and linear shrinkage rate are large, and it is easy to produce shrinkage holes, shrinkage porosity, cracks, deformation and other defects; the inhalation tendency is large, and the air holes are easy to occur [2]. Therefore, the pouring system is required to be able to achieve rapid and stable filling of molten metal, and the pouring system must have a strong slag skimmer ability to filter out oxides and slag. This scheme adopts an open gating system, and the choke cross section is set in the direct flow channel. The calculation of each runner of the gating system adopts the section ratio method. The section ratio of each section is selected according to the characteristics of the open gating system. The section ratio is ∑A: ∑B: ∑C=1:2:2. Where A represents the cross-sectional area of the straight pouring gate, B represents the cross-sectional area of the cross gate and C represents the cross-sectional area of the inside pouring gate.

Comprehensive analysis of the advantages of top-injection, side-injection and bottom-injection gating systems. The bottom-injection gating system can fill the cavity most quickly, fill the mold smoothly, and the molten metal has the least scouring force on the sand core, which is most beneficial to the cavity gas overflow, so the design uses bottom gating system. A glass fiber filter screen is installed at the bottom of the sprue to improve the slag retaining effect. In order to consider the processing of the mold and the flow of metal, the sprue adopts a circular cross section, the runner adopts a trapezoidal cross section, and the inner gate adopts a rectangular cross section. The size of each runner component is calculated by the choke section method, and the size is shown in Table 1.

The calculation method of the choke cross section uses formula 1 [3]:

\[
A = \frac{1000G_L}{\rho_L W \sqrt{2g}}
\]  

Where A is the minimum cross-sectional area of the gating system (cm²), G_L is the weight of the molten metal flowing through the minimum cross-section (kg), \( \rho_L \) is the density of the molten metal at the pouring temperature (g/cm³), W is the main wall thickness of the casting, t is the pouring time (s), g is a constant, taking 980cm/s².

Table 1  dimensions of each pouring gate

| Cross-sectional area (mm²) | straight pouring gate | cross gate | inside pouring gate |
|---------------------------|----------------------|------------|---------------------|
|                           | 94                   | 188        | 188                 |

The design of the feeder aims to reduce the volume of the riser as much as possible on the premise of satisfying the feeding effect of the casting, so as to improve the productivity of the casting and the feeding efficiency of the casting. It should be ensured that the defects of the castings are located in the riser as much as possible, so as to ensure the quality of the castings. According to the analysis of the bare castings, the possible locations of casting defects are preliminarily clarified. Based on this, the top riser is designed as shown in Figure 4.

4. Simulation prediction of casting defect location

The actual field experiment can obtain the feasibility of the casting process plan, and the quality of the casting during the casting production process can also be obtained through the experimental results. However, it is difficult to find the internal defects of the casting through the appearance. In order to solve this problem, castings can only be concluded by accumulating a certain amount of castings and
then dissecting them or testing the castings after forming. Therefore, the cycle is long and blind. Anycasting simulation software is used to simulate and analyze the casting process of castings, which can predict defects in advance, and use the results to improve and optimize the process plan, which can shorten the cycle and save costs. The prediction of the defect location during the casting process of this casting is shown in Figure 5.

**Probabilistic Defect Parameters**

- Defect Parameters = Residual melt modulus, Defect Potential = 0.02142
- Defect Potential = 0.02142

![Casting defect prediction diagram](image)

**Figure 5** Casting defect prediction diagram

It can be judged from the casting defect location prediction map that the casting defect location occurs at the middle and upper part and the bottom thin plate, and the probability of casting defects is predicted to be greater. Aiming at the simulation results of the casting process, it is necessary to optimize and improve the casting process plan. This article starts from the pouring system and the feeding system.

### 5. Casting process optimization

In the original casting process plan, the double-sided bottom-casting pouring system was adopted, which can fill the mold quickly and smoothly, which can meet the filling requirements of aluminum alloy. Because of the defects in the metal bottom plane found in the simulation analysis, the structure of the gate milling in the pouring system is elongated and thinned, the cross-sectional area is increased, and the overlap edge is reduced. The improved pouring system is shown in Figure 6.

According to the casting simulation process of the original plan, the defects of the casting are located on the surface and bottom of the special-shaped plate. This casting defect may be caused by the use of the riser under this scheme, with a sand core in the middle and a metal shape on the outside, so the external solidification quickly leads to a high intermediate temperature, low heat transfer efficiency during the solidification process, and local temperature drops slower. For the two defect positions, a riser is added so that it is in line with the middle riser previously set. Through the set of risers, the casting is fed in two directions to enhance the feeding effect of the special-shaped plate surface and the lower plane. The alloy liquid in the feeder is used to the defective parts are supplemented, and the defects of the castings are finally introduced into the feeder. The improved feeder is shown in Figure 7.
The molten metal flow state during the filling process of the casting after the improved process is shown in Figure 8a. During the filling process, there was no splashing or insufficient pouring of the molten metal. During the entire filling process of molten metal, the improved gating system can achieve the expected filling effect of the casting, smooth filling and complete filling.

The solidification sequence of the improved scheme is shown in Figure 8b. It can be seen from the solidification sequence that the first solidification part of the casting is the surface layer, and the last solidification part is the middle part, which generally satisfies sequential solidification. After adding the bottom feeder, the solidification sequence of the casting is strengthened, so that the final solidification part is located at the feeder. Because the defects produced by castings are generally located in the final solidification part of the castings, they are now transferred to the riser to reduce the risk of defective positions before.

In the previously set casting process plan, the defects of the casting are located on the surface and bottom of the special-shaped plate. After adopting the improved casting process plan, the defects of the casting are improved. As shown in Figure 9, from the X, Y, and Z three cross-sections, casting defects are significantly reduced, achieving the goal of process improvement.
6. Conclusion
According to the characteristics of the aluminum alloy special-shaped parts, the casting process plan is designed for them, and the possible defects are predicted at the side thin wall and the bottom with the help of anycasting software. In order to eliminate these defects, the casting process plan was optimized from the two aspects of the gating system and the feeding system, and finally reached the goal of basically eliminating the casting defects, and a more reasonable casting process plan was determined.

Acknowledgment
This paper is supported by the University-Industry-Research Innovation Foundation of Science and Technology Development Center of Education Ministry (No. 2018A 05021).

References
[1] Peng Yanfeng. Process combination application of laser rapid prototyping and traditional precision casting technology [J]. Aerospace manufacturing technology. 2005(06). (in chinese)
[2] Wang Zaiyou, Wang Zehua. Casting process design and application [M]. Machinery Industry Press, 2016. (in chinese)
[3] Foundry Branch of Chinese Mechanical Engineering Society. Foundry Handbook. Volume 5, Foundry Technology-2nd Edition [M]. Machinery Industry Press, 2003. (in chinese)
[4] Bilek O RL. Rapid prototyping in casting technology: Case study[J]. Annals of Daam & Proceedings. 2011.
[5] Pattnaik S KDBJ. Developments in investment casting process—A review[J]. Journal of Materials Processing Technology. 2012, 212(11):2332-2348.