Optimization of Casting Process of Headstock Based on Numerical Simulation

Yifei Wang *, Zhongde Shan, Haoqin Yang, Xueliang Zhang, Mengmeng Zhao

State Key Laboratory of Advanced Forming Technology and Equipment, China Academy of Machinery Science and Technology Group Co. Ltd, Beijing 100083, China

*yanghaoqin@nuaa.edu.cn

Abstract. In this paper, the casting process optimization design of a certain type of headstock is carried out by numerical simulation technology of casting process. Designed the pouring plan based on theoretical calculation; based on the numerical simulation results, quantitatively designed the riser size, and rationally arranged the pouring riser system based on the equilibrium solidification theory, which can reduce the shrinkage porosity and shrinkage defects in the casting process and increase the process yield; Finally, a sand core production plan is provided based on the precision machining technology of the moldless casting mold, which provides a new idea for the process plan design of complex spindle box castings.

Keywords: casting process; numerical simulation; process optimization.

1. Introduction

Based on computer simulation technology, Procast casting molding software is used to simulate the casting process of machine headstock, analyze the existing problems of existing process methods, and assist in finding out the causes and solutions [1-2] to optimize the headstock casting process. Finally a reasonable casting plan was designed, which improves the surface quality and internal defects of the headstock and greatly improves the casting efficiency.

Headstock is an important part of the machine tool. It is used to arrange the spindle and its corresponding additional mechanisms, and the main functions of that is to support and rotate the spindle to realize the features of spindle start, brake, speed change and reversal. so strict quality requirements for the headstock castings [3]. The casting model is shown in Figure 1. It has a net weight of 95kg and an outline size of 360mm×345mm×450mm. This casting has a large number of curved surfaces and transition fillets, so the structure is complex.
2. Gating system

2.1. gating plan type
There are two ways to classify the gating system: one is based on the proportional relationship of the cross-sectional area of each component, which can be divided into closed, open and semi-closed gating systems; the other is based on the introduction of molten metal into the mold position classification, can be divided into top injection, bottom injection, step injection system, etc. [4].

Closed pouring system refers to a pouring system in which the cross-sectional area of the sprue outlet is greater than the cross-sectional area of the runner outlet, and the cross-sectional area of the runner outlet is greater than the cross-sectional area of the inner runner outlet. During the pouring process of closed pouring system, the liquid flow is in a state of pressurized flow, with strong mold filling ability and large slag blocking ability; it is suitable for pouring iron and other alloys that are not easy to oxidize; The disadvantage is that the flow rate of the inner runner is relatively fast, the scouring force on the mold and the sand core is large, which affects the positioning accuracy of the core and is prone to splashing, entrainment and other undesirable phenomena [5]. However, in combination with this project, the sand mold is designed based on patternless casting precision forming technology, and concavo-convex concerted structures can be processed by the cutting machine to each core unit, which increases the core assembly strength and effectively resists the scouring force caused by the rapid liquid flow. Therefore, classified according to the proportional relationship of the cross-sectional area, we use a closed pouring system for this pouring scheme.

The bottom injection gating system is relatively stable in filling, which can avoid the splashing, oxidation and other casting defects formed by the molten metal; and the air in the cavity is easily discharged in sequence [4]. Considering that the liquid flow filling speed of the closed gating system is large, so that the impact force on the mold and the core is large; In addition, the casting temperature of the iron melt is high, and the sand mold will generate a lot of gas. So the gating system should facilitate exhaust and slow down the liquid flow. Therefore, according to the classification of the position where the molten metal is introduced into the mold, we use a bottom pouring system for this pouring scheme.

2.2. gating plan design and preliminary simulation
Use formula 1 to calculate pouring time[6]

\[ t = \sqrt{G_1} + \frac{3}{5} \sqrt[3]{G_1 \delta} \]

where, \( G_1 \) is the quality of the casting (without the pouring system, the value is 95kg); \( \delta \) is the thickness of the thinnest part of the casting (20mm); Substituting these values, the pouring time is 16.8s

Based on the bottom injection and closed gating system, and by avoiding core hanging, minimizing the number of sand cores, and minimizing the complexity of the sand cores, a pouring scheme is
designed. The opening of the casting is facing downwards, and a pot-shaped sprue cup, a conical straight runner, a trapezoidal runner and two flat inner runners are selected to form a pouring system. In addition, leave six φ10 vent holes on the upper surface of the casting. The cross-sectional area of the inner runner is designed to be 6.8 cm$^2$, the runner area is 8.2 cm$^2$, and the sprue area is 9.6 cm$^2$. The ratio of the cross-sectional area of the sprue, the runner and the inner runner is 1:1.2:1.4. Draw the 3D model of the casting plan, and use the casting process simulation software Procast for numerical simulation. The 3D design of the casting plan and the mesh division diagram are shown in Figure 2.

![Three-dimensional diagram of pouring plan (left) and mesh division diagram (right)](image)

The material selected for this casting is HT300, which is a material with medium to high strength, high wear resistance and vibration damping. Its physical parameters are: liquidus temperature 1245°C, solidus temperature 1129°C, critical solid phase ratio It is 0.7 and the solidification shrinkage volume is 1.0% [7]. Resin sand is selected as the casting material. Part of the thermophysical parameters of HT300 and resin sand, and the change law of the interface heat transfer coefficient between the two are shown in Figure 3.

![Partial thermophysical parameter setting](image)

Carry on numerical simulation to the designed scheme in the Procast, the defect quantity simulation result is shown as in Fig. 4. From the simulation results, it can be seen that the casting defects are concentrated in the hot joints near the spindle hole and the base. The total problem area of the casting is 44.95 cm$^2$, and the total volume of shrinkage cavity is 12.29 cm$^3$; A targeted feeding system should be designed for this casting.
2.3. Feeding system and sand core plan design

2.3.1. Chvorinov modulus calculation method. The modulus of the casting is usually obtained by solving the ratio of the volume of the casting to the heat exchange surface of the casting[8]. In order to accurately obtain the modulus distribution of different parts of the casting, this paper extracts the parameters of the ProCAST solidification result to calculate the Chvorinov thermal modulus. Solve. According to the ProCAST user manual, in a local range, the Chvorinov thermal modulus is approximately equal to the modulus, and the calculation formula is

\[ M \approx \frac{V}{A} = \frac{2}{\pi^2} \left( \frac{T_{at,sol} - T_{mold,ini}}{\rho_{al,sol} \Delta H_{al}} \right) \left( k_{mold,ini} \rho_{mold,ini} C_{p,mold,ini} \right)^{1/2} t_{soi}^{1/2} \]  

Where \( V \) is volume of casting; \( A \) is surface area of the casting from which heat escapes; \( M \) is thermal modulus according to Chvorinov; \( T_{at,sol} \) is solidus temperature of the alloy; \( T_{mold,ini} \) is initial temperature of the mold; \( \rho_{al,sol} \) is alloy density at solidus temperature; \( \Delta H_{al} \) is alloy enthalpy variation from alloy initial temperature to solidus temperature; \( k_{mold,ini} \) is thermal conductivity of the mold at mold initial temperature; \( \rho_{mold,ini} \) is density of the mold at mold initial temperature; \( C_{p,mold,ini} \) is specific heat of the mold at mold initial temperature; \( t_{soi} \) is solidification time[9].

2.3.2. Feeding system design

![Fig.4 Defects statistics results](image1)

![Fig.5 Chvorinov modulus analysis](image2)
The result of Chvorinov modulus calculation is shown in Figure 5. According to the calculation result, the riser should be arranged at the largest hot spot, and the cold iron should be arranged at other hot spots. Extract the average modulus and molten metal volume at the target hot spot, and quantitatively design the riser size, and calculate the required riser modulus to be 1.3cm. Design the riser and arrange it at the largest hot spot near the casting shaft hole; as for other hot spots, chromite sand is used as the mold surface sand to increase the cooling rate of the melt in the corresponding position, cooperate with the riser to change the local solidification temperature field of the casting and eliminate the shrinkage defect in the casting process. The specific layout of the feeding system is shown in Figure 6.

![Fig.6 Schematic diagram of feeding system](image)

### 2.4. Sand core design

The cavity structure of the spindle box casting is relatively complicated, and it is difficult to directly manufacture the corresponding sand core, and the dimensional accuracy is difficult to guarantee. In response to this problem, this solution divides the complex structure sand core into sub-units according to the geometric characteristics of the cavity, and uses digital moldless casting precision forming technology to directly cut each core unit driven by the 3D CAD model. The technology reduce the difficulty of core production and improves the dimensional accuracy [10].

The sand core assembly scheme is shown in Figure 7(a). The unit bodies of the sand core are mainly positioned and connected by a pin hole structure. In view of the large volume, large mass, and irregular shape of the three sand core units below, this solution has designed a threaded clamping device to form a reliable clamping force. Figure 7(b) shows the sand core after assembly.

![Fig.7 Sand core solution](image)
3. Simulation results and analysis
Numerical simulation is performed again on the optimized scheme. The filling process is shown in Figure 8. It can be seen that after the optimized scheme, during the filling process with the pouring temperature of 1420℃ and the pouring time of 17 s, the rising speed of the metal liquid level is about 17.5 mm/s. The filling of high-temperature molten metal is stable, the height difference of different parts is not obvious, there is no turbulence caused by the large flow of liquid phase impacting the wall during the filling process, and there is no obvious liquid surface splash, entrainment and insufficient pouring. The distribution diagram of shrinkage cavity defects in castings is shown in Figure 9. It can be seen that the feeding system has played a great role in successfully transferring all casting defects to the pouring riser system or casting vent holes. The optimized process plan successfully eliminated the original process Shrinkage porosity and shrinkage cavity defects in the scheme.

Fig.8 Filling process simulation
4. Summary

(1) Based on the analysis of the headstock structure and usage requirements, based on theoretical calculations, a pouring plan for gray iron headstock castings is proposed, and simulation is carried out with the aid of CAD/CAE software. By rationally designing the feeding system and changing the solidification sequence of the castings, the effective feeding of the defect position is realized.

(2) Through the application of numerical simulation technology, we extract the average modulus and molten metal volume at the hot spot in the solidification simulation results, quantitatively design the feeder size, and provide a sand core production plan based on the precision machining technology of moldless casting. The thesis provides a new idea for the process design of complex spindle box castings.

Acknowledgements

This paper is supported by The National Science Fund for Distinguished Young Scholars of China. (No. 51525503)

References

[1] Zhang Fuquan, Wang Yang, Zhou Yiwu, et al. Numerical simulation of casting process of large section ductile iron and prediction of shrinkage. Foundry technology, 2013, 34(8): 1027-1030.

[2] Gaojian Li. The Optimization Simulation of Casting Process for Compressor Crosshead. International Journal of Computational and Engineering, 2019, 14-16.

[3] Jiang Chang, Xiang Siyu. Numerical Simulation and Optimization of Casting Process of Headstock Based on ProCAST. Foundry Engineering, 2020, 44(05): 40-43.

[4] Zhao Chengzhi, Zhang Hexin. Casting process design and practice. China Machine Press, 2017.

[5] Li Chenxi. Casting technology and tooling design. Chemical Industry Press, 2014.

[6] Peng Xianping, LIU Wen-chuan. Study on Calculation Formula of Effective Pouring Time for Gray Iron Castings Foundry technology, 2010, 31(04): 396-400.

[7] Fan Peng. Modern cast iron technology. Beijing: China Machine Press, 2019.

[8] Lin Qiquan, Deng Zhiru, Dong Wenzheng, Zhou Qiaoying. Technology design for complex gray cast iron part by the numerical simulation. Materials Science & Technology, 2016, 24(05): 58-64.

[9] ProCAST. ProCAST User Manual. ESI Group, 2013.

[10] Shan Zhongde. Patternless casting. Beijing: China Machine Press, 2017.