www.czasopisma.pan.pl www.journals.pan.pl

ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2023
Issue 1/2023

83 – 102

10.24425/afe.2023.144284

12/1

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Influence of Asymmetrical Bending Pipe with Different Gating Systems on Low-Pressure Metal Mold Casting

Ning Wang [a], **Rong Li** [a, *], **ZiQi Zhang** [a], **Qi Zeng** [b]
[a] School of Mechanical & Electrical Engineering, Guizhou Normal University
[b] Guiyang Huaheng Mechanical Manufacture CO.,LTD, China
* Corresponding author. E-mail address: lirong9242001@163.com

Received 10.10.2022; accepted in revised form 13.12.2022; available online 23.03.2023

Abstract

To prepare a high-quality asymmetrical bending pipe of aluminum alloy by casting, the parting surfaces of the asymmetrical parts were determined based on the characteristics of the parts. Also, the forming process was designed and calculated. After that, the different types of gating systems were designed and the casting process was calculated by ProCAST, and then the influence of different casting gating systems on asymmetrical bending pipes was analyzed. The simulation results show that in the solidification process, although the filling speed of the single runner was slow, but the filling was stable. The gating system with a single runner-round flange filling system would lead to being more uniform for filling flow field and be sequential solidification of temperature field distribution, and stronger of the feeding ability. During the solidification process, the solid phase ratio of the single runner-round flange casting system is larger, and the shrinkage volume is smaller, which made the quality of castings better. Finally, a metal mold and core were made to cast a perfect asymmetric bending pipe of aluminum alloy product in a die casting machine. So the single runner-round flange filling system is suitable for asymmetrical bending pipe casting.

Keywords: Casting simulation, Gating system, Asymmetric asymmetrical bending pipe, Low-pressure casting, Metal mold

1. Introduction

The low-pressure casting was a high performance on precision and metal utilization rate. It was suitable for the forming of large thin-walled castings [1-5]. The performance of metal mold casting was high dimensional accuracy, fine grain and stable quality, but there are also problems such as too fast metal cooling speed and difficulty in gas discharge in the mold [6, 7]. The casting of low-pressure metal mold was well mechanical properties and surface finish, which combined the advantages of low-pressure and metal mold casting. But the casting defects are easy to occur, such as shrinkage porosity and shrinkage [8]. To reduce the defects of low-pressure casting, many scholars have optimized the forming process based on numerical simulation to reduce the occurrence of the defects. ProCAST soft was used to simulate the defects such as insufficient pouring and pores for complex thin-walled sand mold in low-pressure casting to achieve the effect of process optimization by Xu Xiaolin et al. [9, 10]. Li Qiang Zhang et al. [11, 12] determined the feasibility of numerical simulation during low-pressure casting of A356 aluminum alloy by combining ProCAST software and thin-walled parts with a wall thickness of less than 2 mm. MAGMA software was used to formulate the low-pressure casting pressure curve of aluminum alloy and verified the production by Liu Jidong et al. [13], which indicated that a reasonable pressure curve can ensure the stability of the casting quality. Liu Jiguang et al. [14] used the ProCAST software to perform multiple simulations of low-pressure casting with a multi-function display console to optimize parameters and reduce the defects of porosity and shrinkage in the casting. ProCAST and NFS were used to simulate the whole process of low-pressure casting to limit defects in components and provide the results to the production site by Amir M Horr et al. [15]. Also, Manthan Dhisale et al. [16] used FLOW 3D software simulation to obtain a method to control cooling channel parameters to reduce shrinkage porosity. Therefore, the use of numerical simulation software can reduce the incidence of defects in the low-pressure casting process effectively and improve the availability and reliability of the casting process design.

This paper is aimed at the needs of asymmetric bends used in the petroleum, chemical and marine industries in terms of connecting strength, lightweighting and defect-free. 3D modeling and casting simulation software (ProCAST) is used to simulate and analyze the asymmetric aluminum alloy bends in low pressure metal casting. The general method of reasonable parting surface for asymmetric bent pipe castings is determined through the research of this paper, and the influence on the casting quality during the pouring process and solidification of asymmetric bent pipe castings under different casting systems is analyzed. Lastly, the simulation results are verified by conducting actual casting tests to determine the best process solution for asymmetric bent pipe castings.

2. Process Parameter Analysis and Pouring System Design

2.1. Part Features and Process Analysis

Part of the casting is shown in Figure 1. The casting had a height of 305mm, a length of 448mm and a volume of 1118 cm^3. There are both flanges at the ends, one is square and the other is round. The side length of the square flange is 180mm, and the diameter of the round flange is 225mm. The transition from a round flange to a square is asymmetrical. The material is used as a cast aluminum alloy (ZL105A). According to the density of aluminum alloy material (2.68g/cm^3), the weight is about 3kg. This part is a thin-walled bending pipe with an asymmetric structure, and the key positions of casting are the connecting flange and internal bending. Therefore, this part needs to be mass produced by the low-pressure casting by the metal mold.

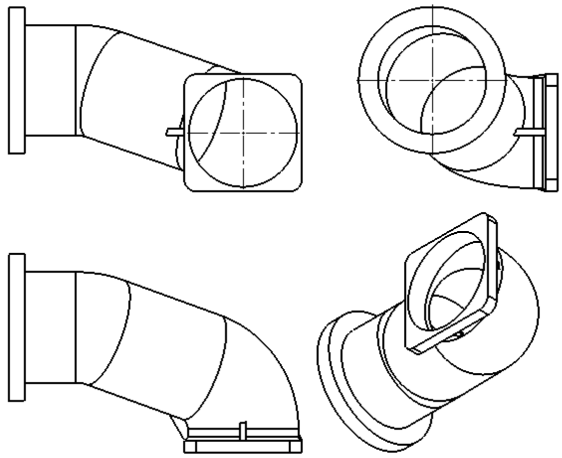


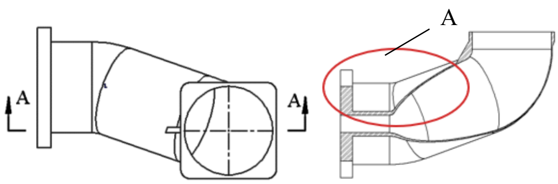
Fig. 1. Casting parts diagram

2.2. Molding Process Analysis and Design

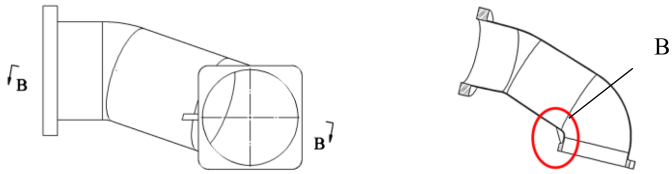
The forming quality of the casting part is impacted by the forming process. Based on the analysis of the parameters of the part, the parting surface of asymmetric parts was analyzed, and the pressure and filling speed also be calculated. And then the different gating systems were designed for simulation analysis.

2.2.1. Parting surface

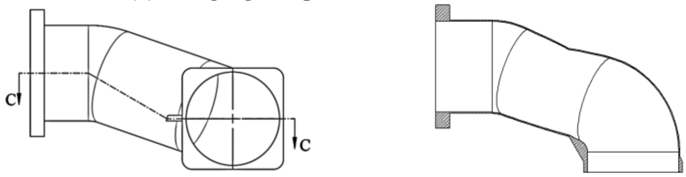
The selection of the parting surface has a direct impact on the part mold modelling, mold opening and pickup part, core installation, riser and cold iron design [17]. According to the part shape, which is an asymmetrical thin-walled pipe with different flanges at both ends, the introduction position of the gating system needs to be set on both flange ends. And then, the straight parting surface, inclined parting surface and stepped parting surface are designed based on the introduction position, as shown in Figure 2. With a straight parting surface, the thin-walled and rounded flanges of the casting (area A in Figure 2-a) will not be able to be removed from the metal mold smoothly, or even damage the mold. Therefore, the parting surface cannot normally realize mold opening and mold taking, as shown in Figure 2-a. With the inclined parting surface, the reinforcing ribs at the square flange of the mold cannot be directly formed in the mold. After the casting is solidified, the reinforcing rib cannot be taken out of the metal mold (area B in Figure 2-a). In addition, the parting surface will increase the difficulty of mold manufacturing, thereby increasing the cost of manufacturing, as shown in Figure 2-b. Finally, a stepped parting surface was designed to ensure that the casting can be removed from the mold after solidification without damaging the mold. It was dependent on the decreasing trend of the size of the C-C section of the asymmetric parts and the characteristics of the section structure, as shown in Figure 2-c.



(a) Straight line parting surface and section view



(b) Oblique parting surface and section view



(c) Step parting surface and section view

Fig. 2. Parts parting surface selection

2.2.2. Calculation of pressure and filling speed

To mass-produce, pressure casting is selected, and the filling pressure of the gating system is calculated according to formula (1). [13].

$$P=(H\gamma\mu/13.6)\times 133.3 \qquad (1)$$

Where, P is filling pressure, Pa; H is the total height of alloy liquid rising from liquid level to top of casting, mm; γ is the density of alloy liquid at pouring temperature, kg/dm^3; μ is the resistance coefficient is generally taken as μ=1.0~1.5.

Among them, H is determined to be 1730mm according to the height of the liquid riser of the field equipment and the mold. The material of casting is ZL105A aluminum alloy, and the density of aluminum is 2.68kg/dm^3 at 710℃. Taking into account the comprehensive coefficient of various resistances and the supercharging factor, μ=1.1. Substitute the above values into formula (1), and convert the unit to mbar (1mbar=10^{2}Pa), and calculate the filling pressure $P \approx 500$ mbar.

During filling the cavity with molten metal, too slow a speed will cause defects such as cold insulation and insufficient pouring of the casting. So it is necessary to be stable and quick during the filling process. The H.M. Culkin formula (2) is used to calculate the filling speed [18].

$$v_{fmin}=0.22\times\sqrt{h}/\delta\ln(t_p/380) \qquad (2)$$

Where, v_{fmin} is the average rising speed (along the height of the casting) of the molten metal in the mold, cm·s^{-1}; h is the height of the casting, cm; δ is the wall thickness of the casting, cm; t_p is the pouring temperature of the alloy, ℃.

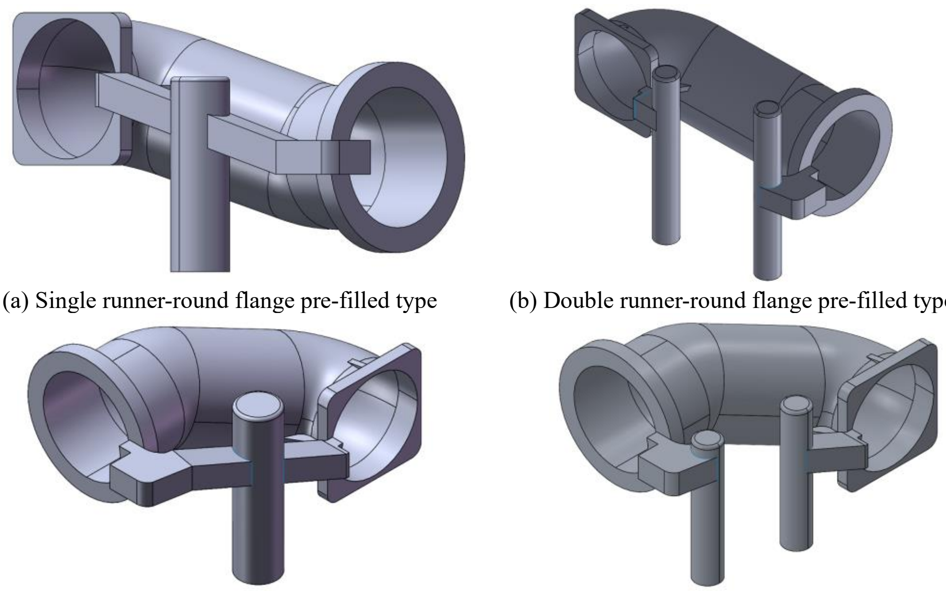
The pouring temperature of the ZL105A alloy is t_p=710℃, the wall thickness of the casting is δ=5mm, and the height of the casting is h=284mm. Substitute the values into the formula (2), and convert the unit to mm·s^{-1} to get the filling speed $v_{fmin}\approx$37.5 mm·s^{-1}. So, the filling time: $t_f=h/v_{fmin}$=7.6s.

The final filling pressure of this casting is $P\approx$500 mbar, the filling speed is $v_{fmin}\approx$37.5 mm·s^{-1}, and the filling time is $t_f=h/v_{fmin}$=7.6s.

2.3. Schematic Design and Dimension Calculation of Pouring System

2.3.1. Design of gating system

To verify the influence of different types of gating systems on the molding of parts, based on the characteristics of asymmetric parts, the different shapes, the sizes of flanges at both ends and the different order of liquid inlet of the flanges, a single sprue entrance (a single gate is injected into two cross runners) and a double sprue entrance (two gates are injected directly into the part) are designed. And both sprue entrances are designed. Based on the state of the runner and the sequence of the liquid inlet of the flange, four kinds of gating systems are designed: "Single runner-round flange pre-filled type", "Single runner-square flange pre-filled type", "Double runner-round flange pre-filled type" and "Double runner-square flange pre-filled type", as shown in Figure 3.



(a) Single runner-round flange pre-filled type (b) Double runner-round flange pre-filled type

(c) Single runner-square flange pre-filled type (d) Double runner-square flange pre-filled type

Fig. 3. Schematic diagram of different gating systems

2.3.2. Dimensional calculation of gating system

1. Determination of the cross-sectional area of the runner

Due to the casting characteristics of low-pressure casting, the inner gate can be regarded as a riser, and the cubic equation method for the riser is used to determine the size of the inner gate in low-pressure casting [18, 19], the formula (3) is as follows:

$$d^3\text{-}k_1d^2\text{-}k_2=0 \tag{3}$$

In the formula: d is the diameter of the riser; k_1 and k_2 are the parameter coefficients.

Equation (3) is the general formula of the riser equation, which applies to all kinds of risers, except that different forms of risers have different k_1 and k_2 values. After using the cubic equation to calculate the riser to determine the cross-sectional area of the runner, formula (4) was used to check the size of the runner and make corrections based on practice after the mold trial [18].

$$A_g=W/\rho vt \tag{4}$$

Where, A_g is the cross-sectional area of the runner, cm^2; W is the weight of the casting, g; ρ is the alloy density, g·cm^{-3}; v is the linear velocity at the outlet of the sprue, cm·s^{-1}. When $v\leq150$ cm·s^{-1}, the smooth filling can be achieved.t is the filling time, s; calculated according to the rising linear velocity of the alloy in the mold. That is: $t=h/v_l$ (h is the cavity height, cm), v_l=1~6cm·s^{-1}, and the upper limit of complex thin-walled parts is taken.

Calculation of the cross-sectional area of the runner: the weight of the casting W=3000g, the density of aluminum alloy liquid at 710℃ is ρ=2.68 g·cm^{-3}, Filling time t_f=7.6s when the maximum value is obtained according to the linear velocity $A_g=W/\rho vt$=2996/(2.68×150×7.6) =0.98cm^2. After correction using the calculated filling speed, we get $\sum A_g\approx39.22$cm^2, take as $\sum A_g$=39 cm^2.

Based on the casting structure and machining principles, the non-machined surface of the flange is selected as the position of the inner gate. After the section size of the ingate was determined, the cross-sectional area of the runner was selected.

2. Determination of cross-sectional area of runner and sprue

In this study, ZL105A aluminum alloy was used, which belongs to the easy-oxidizing alloy. To give full play to the feeding effect of the gating system in the low-pressure casting process, it is necessary to ensure $A_i<A_r<A_s$. the cross-sectional size of the in-runner can be calculated according to the formula, and then the cross-section area of the runner and sprue can be selected according to the ratio [17]. The ratio is A_i: A_r: A_s = (2~2.3): (1.5~1.7): 1. Therefore, the casting simulation in this study adopts the cross-section ratio as A_i: A_r: A_s =2:1.5:1. The dimensions of each runner corresponding to the gating system are: Inner runner area: $\sum A_g$ =39cm^2, A_g=39/2 cm^2=19.5cm^2. Sprue (riser tube) area: $A_{ir}=A_g$ ×2=39cm^2. Runner area: $A_{ru}=A_g$×1.5=29cm^2.

3. Verification of the sprue area

The linear velocity of the molten metal would be impacted by the cross-sectional of the riser pipe of the pouring machine in the cavity. It also affected the filling stability of the low-pressure metal casting. Therefore, the cross-sectional dimensions of the gating system need to be checked to ensure that the molten casting metal behaves as "laminar flow" during the filling process. The outlet area of the riser pipe can be calculated using formula (5) [18].

$$F\geq1000G/Z\mu\gamma\sqrt{2gH} \tag{5}$$

Where F is the outlet area of the riser pipe, cm^2; G is the weight of molten metal required for the casting, kg; Z is the filling time of the casting, s; μ is the flow resistance coefficient of the molten metal at this temperature, and the resistance coefficient of the aluminum alloy at 710 ℃ is 0.3 ~ 0.4; γ is the specific gravity of the molten metal at this temperature, $g \cdot cm^{-3}$; g is the acceleration of gravity, 980 $cm \cdot s^{-2}$; H is the height that the molten metal needs to rise, cm.

The linear velocity of the molten metal should not exceed 1.5~1.6 $m \cdot s^{-1}$ [20] to avoid the eddy current scouring the molten metal during the pouring and filling process, resulting in a turbulent flow. By controlling the outlet area of the riser, the filling speed after passing through the outlet of the riser is controlled [18], which can be calculated by equation (6).

$$\omega \leq v/\ (F \cdot Z) \tag{6}$$

Where, ω is the linear velocity of the metal liquid flow in the cavity, $cm \cdot s^{-1}$; v is the volume of molten metal passing through the riser outlet, cm^3; F is the cross-sectional area at the outlet of the riser pipe, cm^2; Z is the filling time of the molten metal, s.

The weight of the casting is G=3kg, the destiny of aluminum at 710℃ is γ =2.68 $g \cdot cm^{-3}$, the filling time Z=7.6s, the resistance coefficient of the alloy is μ=0.4, the height H=225cm that is a distance of the molten metal rising, is calculated according to the formula $F \geq 1000G/Z\mu\gamma\sqrt{2gH}$ (cm^2), and $F \geq 0.55cm^2$ is obtained. As verified by the formula $\omega \leq v/\ (F \cdot Z)$ ($cm \cdot s^{-1}$), where the linear velocity of the molten metal in the cavity is ω=3.75 $cm \cdot s^{-1}$, the volume of the molten metal passing through the outlet of the riser is v=1118 cm^3. It is obtained that $F \leq 39.2cm^2$, and the value range of the outlet area of the riser pipe is $0.55cm^2 \leq F \leq 39.2cm^2$.

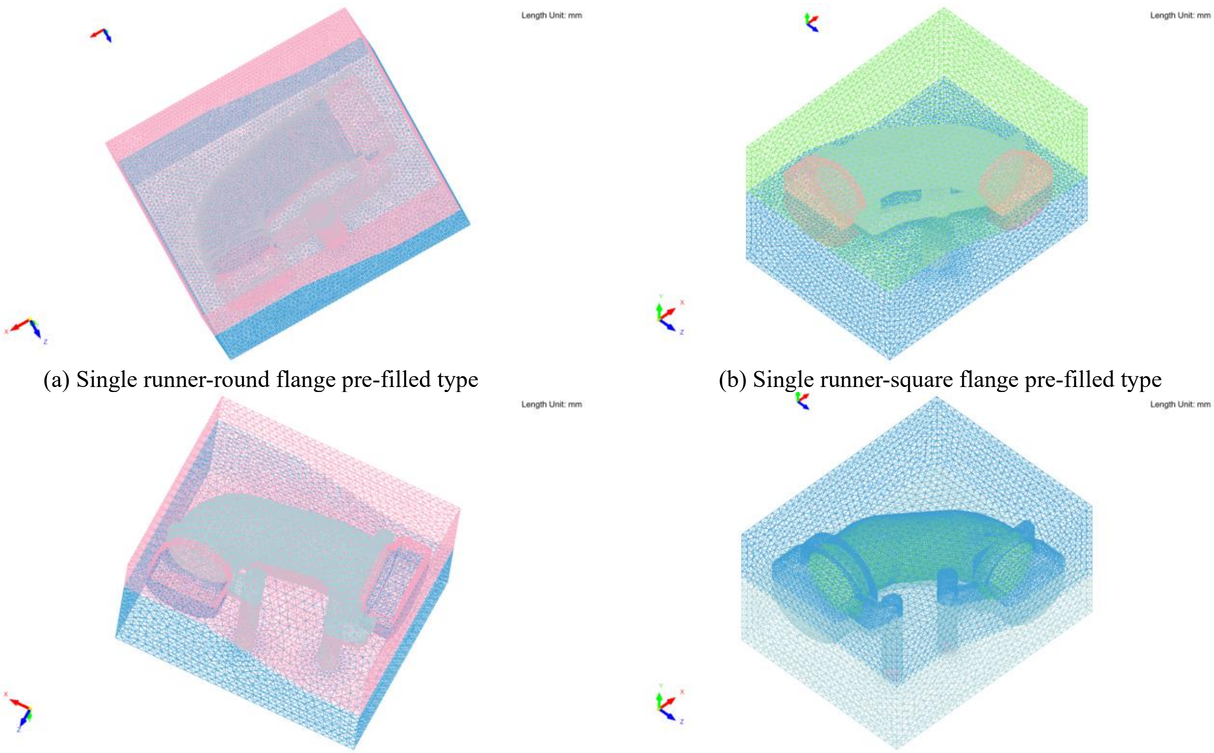
So, the casting sprue area of the casting system of this part is 39 cm^2, which is within the value range of the outlet interface of the riser pipe, so the size of the runners was satisfying the gating system.

3. Simulation Calculation Process and Result Analysis

Before performing the simulation, the following boundary conditions need to be set for the casting process.According to the casting manual [17], the heat transfer coefficient between the core and the casting was chosen to be 500 W/ ($m^2 \cdot K$), and the heat transfer coefficient between the casting and the metal mold was chosen to be 1000 W/ ($m^2 \cdot K$). The simulation was stopped when the casting temperature dropped to 400°C under natural air cooling conditions or the simulation time reached 310s.

3.1. Simulation Calculation Process

In the casting simulation process, the external model is imported into the ProCAST simulation software for pre-processing of the simulation calculation, including the inspection and correction of the imported product model and the division and repair of the surface/body mesh. Then set the parameters in the software based on the pouring method and simulate the pouring process. Product model meshing is shown in Figure 4.



(a) Single runner-round flange pre-filled type (b) Single runner-square flange pre-filled type

(c) Double runner-round flange pre-filled type (d) Double runner-square flange pre-filled type

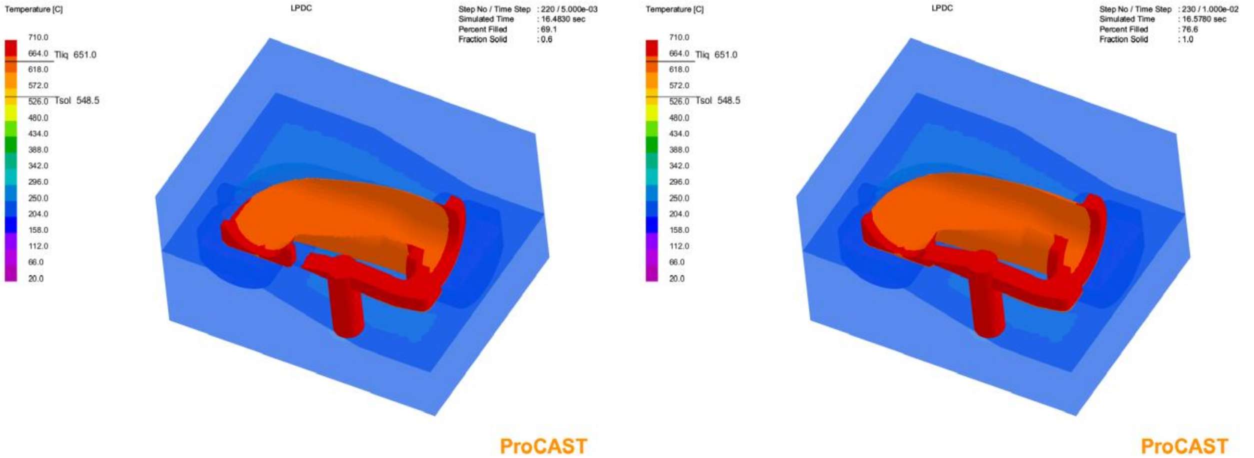
Fig. 4. Product model grid

3.2. Effects of different gating systems on the filling process

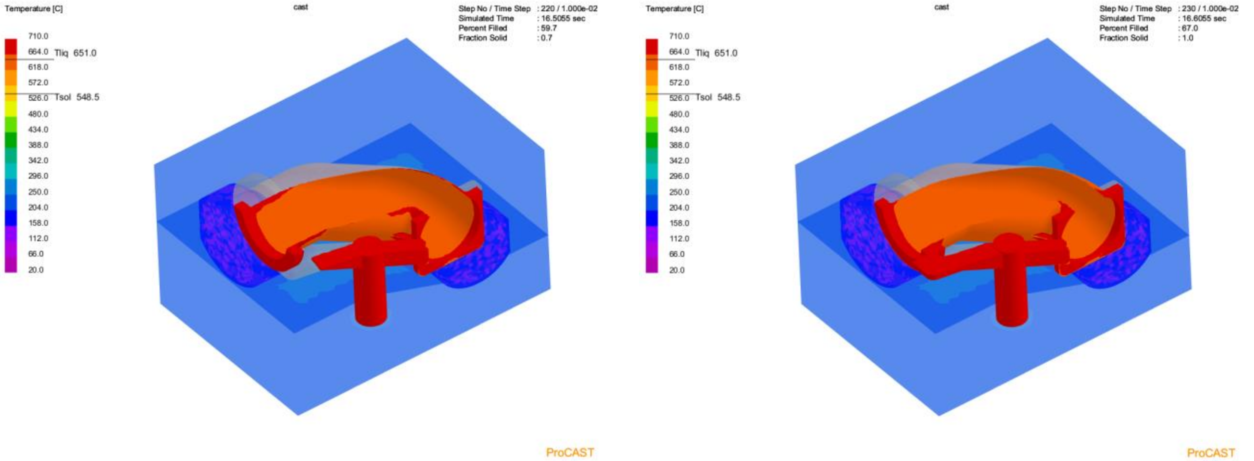
This research is mainly aimed at the flow field state and its influence on product quality under different gating system states [21, 22]. The gating system has a great influence on the quality of the castings, which is easy to cause various types of casting defects. The melt flow field, temperature field and the location of the hot node were analyzed during the filling process, and the optimal filling scheme was determined for the asymmetrical bending pipe.

3.2.1. Flow field state

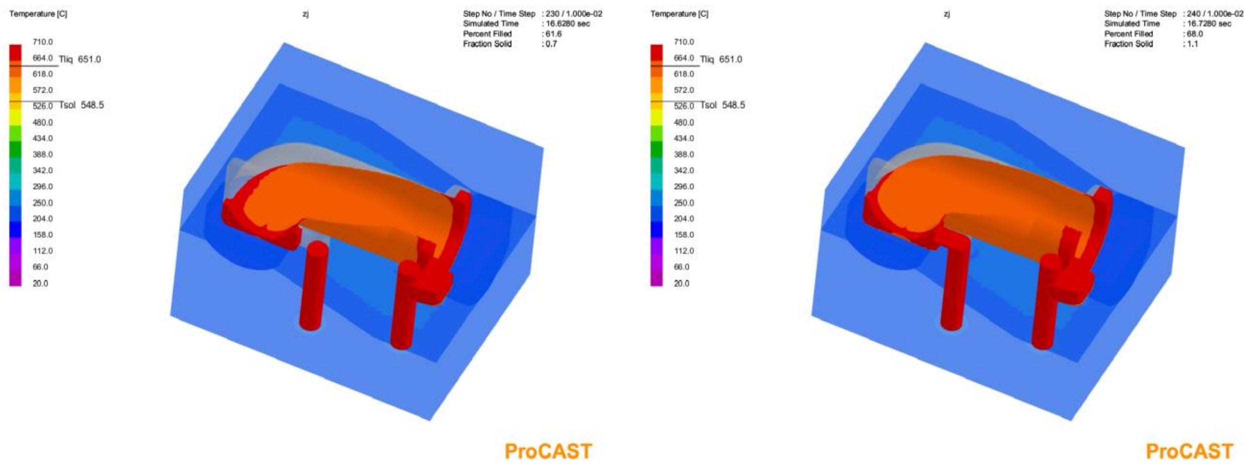
The flow field of the casting obtained by using different pouring schemes is shown in Figure 5. From the overall simulation results, the filling process of the casting takes a short time, the speed is fast, the filling is stable, and there is no obvious air entrainment and no turbulent state.



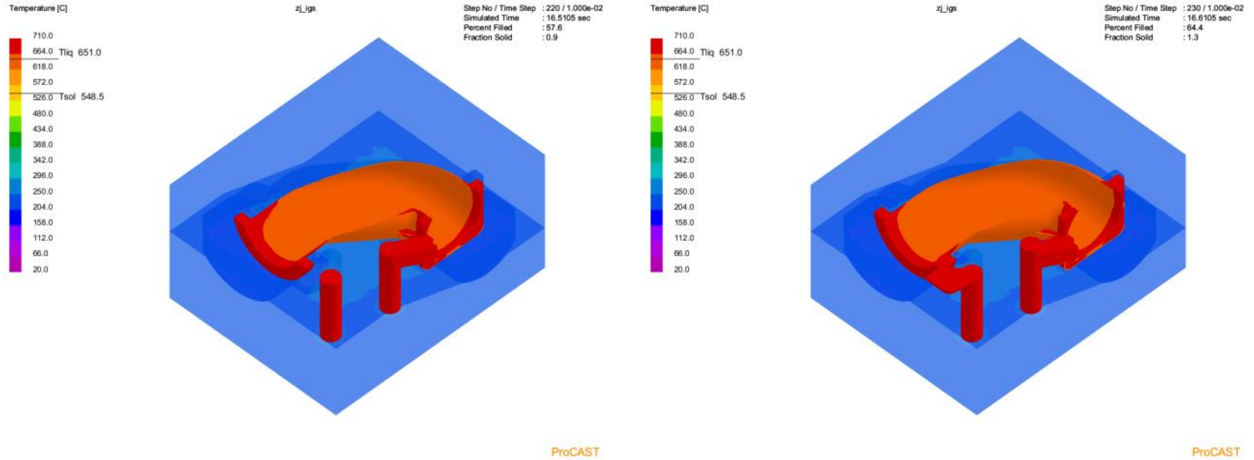
(a) Single runner-round flange pre-filled type



(b) Single runner-square flange pre-filled type



(c) Double runner-round flange pre-filled type



(d) Double runner-square flange pre-filled type

Fig. 5. Filling process of different pouring schemes

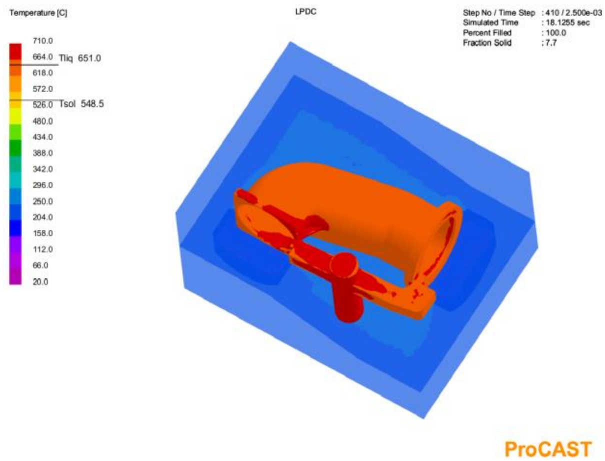
It can be seen from Figure 5-a and Figure 5-b that the single-channel gating system is used, the liquid level in the cavity rises steadily, the rising speed is slow, and the air and slag in the cavity are easily discharged. As can be seen from Figure 5-c and Figure 5-d, the lengths of the two sprues are the same, and the heights of the liquid inlets are different, so there will be differences in the sequence of the molten metal entering the cavity. Under the action of pressure, the molten metal of both liquid inlets will meet at the secondary liquid inlet. Therefore, the single runner gating system can effectively avoid slag inclusion defects during the filling process.

Also, you can see from Figure 5-a and Figure 5-c that under the same filling height and pressure, the filling speed of the double runner becomes smaller, the solidification area of the casting becomes larger during the filling process, and the molten metal is still filled at a stable speed. However, when the inlet of secondary liquid starts to feed liquid, air and slag defects are shown at the secondary liquid inlet during the filling process. There is a slope in the runner of the single-runner gating system, and the oxide inclusions would be discharged from the cavity as the molten metal converges [22, 23], effectively avoiding the occurrence of defects such as oxidation inclusion. The same difference appears in Figures 5-b and 5-d, but with a shorter sprue in the double runner. Under the same pressure, the length of the sprue is shortened, and the filling time of the sprue will be shortened, but the pressure inside the cavity cannot be kept balanced, and the filling speed will be slowed down, resulting in a longer filling time.

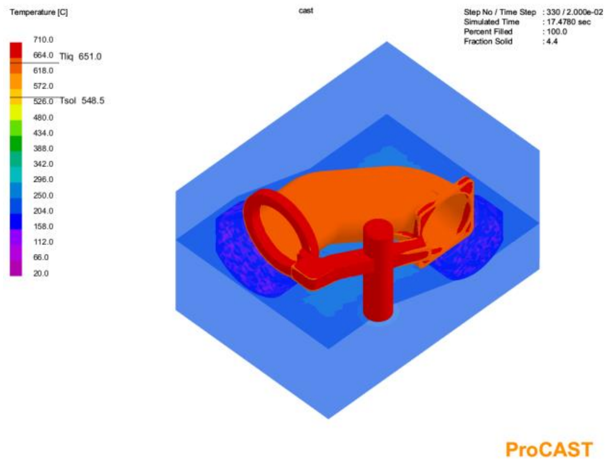
From the above results, the flow field of the molten metal in the cavity of the asymmetric bending can be understood through the flow field during the casting process. The characteristics of the molten metal fluid are obtained through the temperature range of the alloy phase transformation. Uncontrolled fluid flow can cause turbulence such that air and slag are trapped inside the cavity during fluid filling, resulting in larger oxide defects [16]. During the filling process of the double runner gating system, the filling speed and time will change with the length of the casting sprue, which will affect the cooling speed of the casting and even affect the solidification sequence of the casting. During the filling process of the single runner, due to the slope of the runner, can ensure the smooth discharge of defects such as air and slag inclusion. In the single runner-square flange pre-filling scheme, the fluid will converge at the top of the circular flange, and it is difficult for the air to be discharged in time at this time. For asymmetrical bindings, the structural features of the casting itself make it difficult to remove defects during the casting process, resulting in difficulty in forming the casting. However, the single-runner-round flange pre-filling casting scheme ensures the stable filling of the cavity by the molten metal during the filling process. The slope of the runner can be used to discharge air and other factors that are not conducive to the formation of castings in time under the action of pressure, thereby improving the surface quality of the castings.

3.2.2. Temperature field status

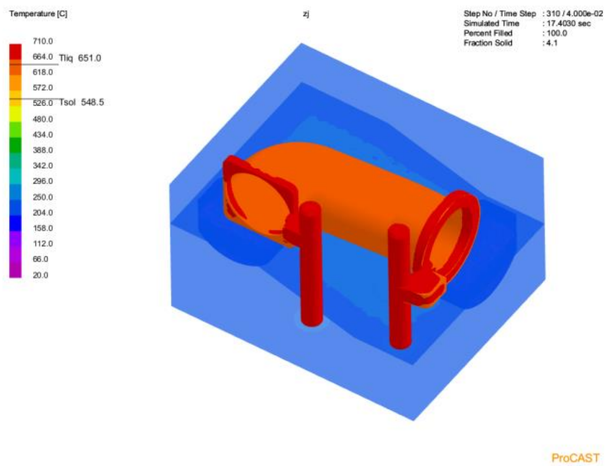
Figure 6 shows the temperature field of the casting after filling with different pouring schemes. From the simulation results, when the casting is filled, the solid phase has appeared in the local thin wall of the casting far away from the gate.



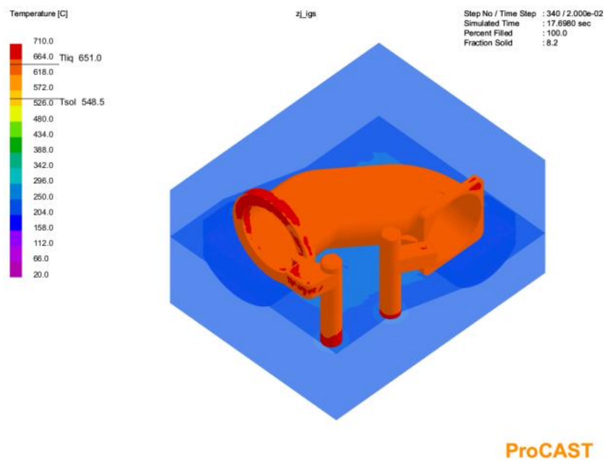
(a) Single runner-round flange pre-filled type



(b) Single runner-square flange pre-filled type



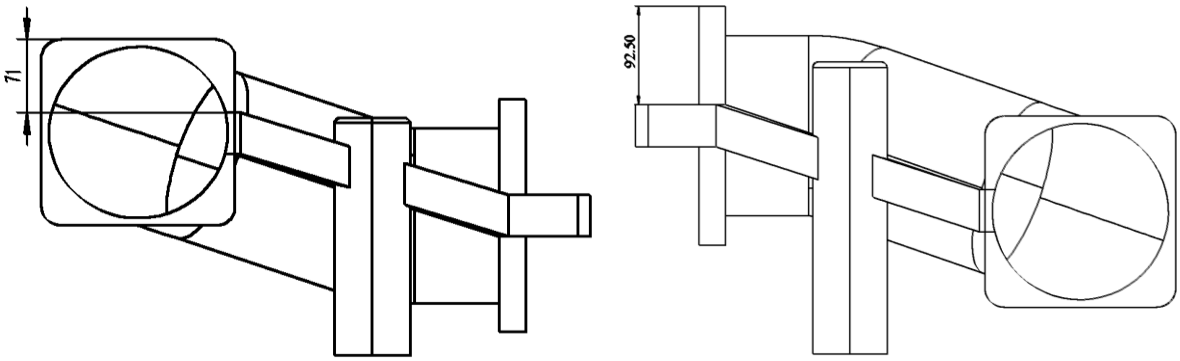
(c) Double runner-round flange pre-filled type



(d) Double runner-square flange pre-filled type

Fig. 6. Temperature distribution of different pouring schemes

It can be seen from Figure 6-a and Figure 6-b that when the cavity is filled through the liquid inlet, the overall liquid area of the casting in the square flange pre-filling scheme is larger. In particular, the overall temperature at the circular flange of the secondary liquid inlet is relatively high, which is unfavourable for the solidification state of the flange. Due to the size difference between the circular flange and the square flange, the distance from the second liquid inlet to the top of the casting will be different, and the filling speed and filling time will also change accordingly, resulting in the need for larger filling pressure. After measuring the distance between the liquid inlet and the top of the cavity (as shown in Figure 7-a and Figure 7-b), it can be seen that the square flange pre-filling scheme needs to provide a filling pressure that is 21.5mm higher than that in the round flange pre-filling scheme.



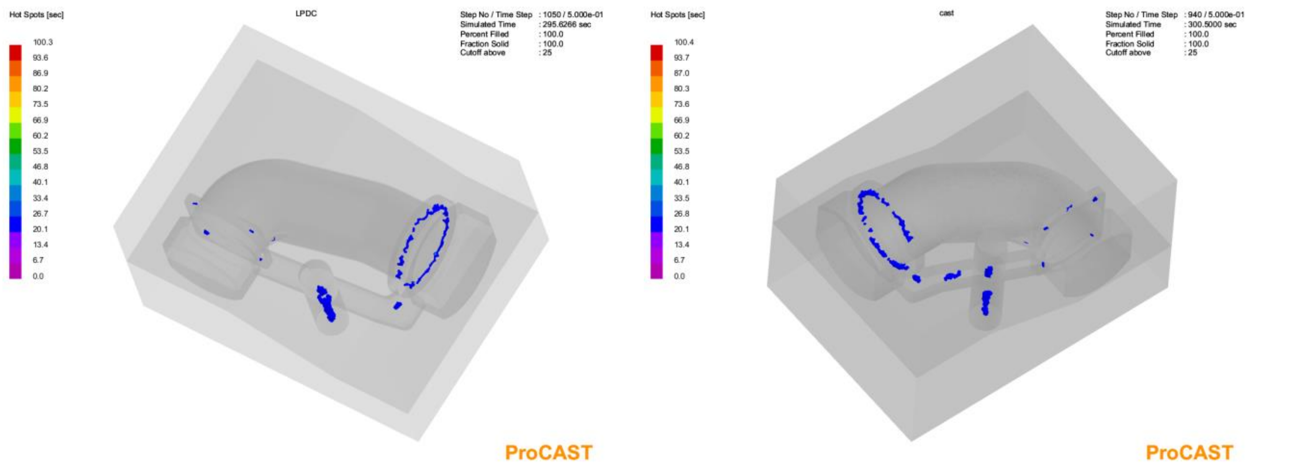
(a) Single runner-round flange pre-filled type (b) Single runner-square flange pre-filled type

Fig. 7. The distance from the liquid inlet to the top of the cavity for different pouring schemes

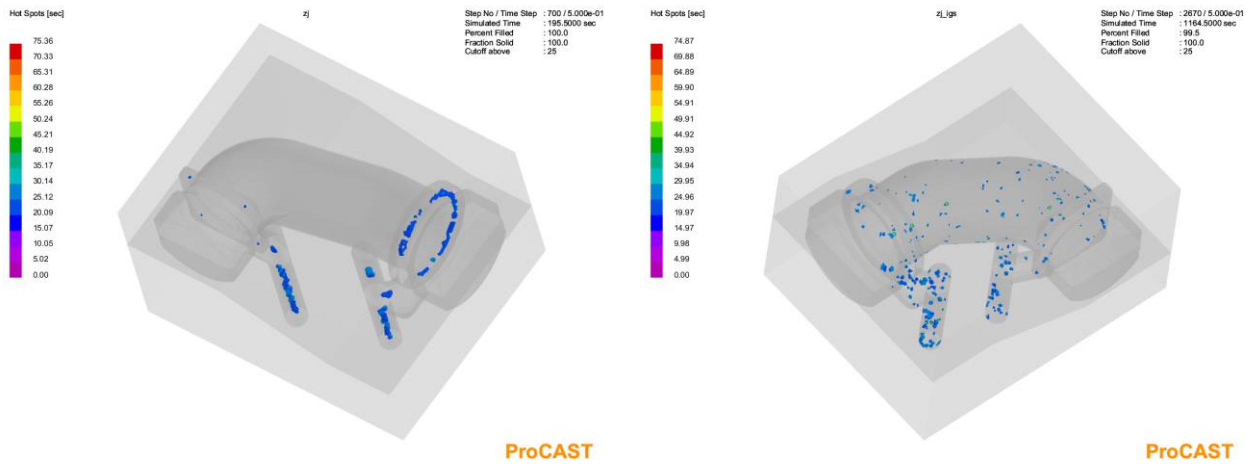
As can be seen from Figure 6-c and Figure 6-d, when the sprue is higher than the overall height of the casting, the overall temperature gradient of the casting above the liquidus line (651°C) will move towards the sprue, ensuring the feeding channel of the gating system to the casting. When the sprue is higher than the liquid inlet and lower than the overall height of the casting, the overall temperature gradient of the casting above the liquidus line is the circular flange (height higher than the liquid inlet) part of the casting. At this time, the feeding of the casting is limited to a certain extent, and even the circular flange is insufficient due to the cooling shrinkage of the metal [24, 25]. Therefore, the use of a single runner gating system can ensure the feeding capacity of the gating system to a certain extent. Under the action of pressure, the molten metal inside the gating system can effectively supplement the cooling shrinkage of the metal in the flange part to avoid defects such as insufficient pouring.

It can be seen from Figure 6-a and Figure 6-c that when the gating system is inconsistent, the liquid phase area at the circular flange of the single runner is smaller. However, the height of the sprue affects the rate of reduction of the casting temperature, thereby affecting the feeding ability of the casting. Since the sprue in the double sprue gating system is independently filled with liquid, when the second liquid inlet starts to enter the liquid, the cavity is filled at the same time by both liquid inlets, and the square flange is partially filled. After the cavity is filled, the high-temperature area of the flanges at both ends is formed due to the rapid decrease in the temperature of the thin wall, which ultimately affects the solidification time of the casting. From Figure 6-b and Figure 6-d, it can be seen that in the double-runner gating system, the liquid phase area is smaller, and the temperature distribution is more uniform. However, the area of the metal liquid phase at the circular flange and the square flange is significantly higher than that of the single runner, and the rate of temperature reduction is significantly faster. This may be because both sprues in the double runner are independent of each other, and the height of the sprue does not guarantee the feeding ability of the gating system to the casting. Therefore, the pre-filled circular flange ensures that the gradient direction of the temperature field faces the gating system, which can achieve the purpose of sequential solidification, ensure the feeding ability of the gating system, and obtain aluminum alloy castings with dense internal structure.

The location where the casting filling temperature is higher will form hotspots. The distribution of the casting hotspots obtained by different pouring schemes for this part is shown in Figure 8.



(a) Single runner-round flange pre-filled type (b) Single runner-square flange pre-filled type



(c) Double runner-round flange pre-filled type (d) Double runner-square flange pre-filled type

Fig. 8. Distribution of thermal nodes for different pouring schemes

Figure 8-a and Figure 8-b respectively show the distribution of hotspots after filling the two filling schemes with a single runner. The average results of the round flange pre-filled type and the square flange pre-filled type hotspots are 13.63s and 15.11s, respectively. The distribution positions of the hotspots are concentrated on the round flange and square flange of the casting. The average results for the round flange prefill are significantly smaller, indicating that the distance from the second inlet to the top of the casting increases the average time of the hotspots, preventing the gating system from feeding. The distribution of hotspots after the filling of the two filling schemes with double runners is shown in Figures 8-c and Figure 8-d. The average results of the round flange pre-filled type and the square flange pre-filled type hotspots are 15.28s and 15.73s, respectively. In the double runner round flange pre-filling scheme, the hotspots are mainly distributed on the square flange and the round flange of the casting. In square flange pre-filling, the hotspots are distributed over the entire casting of casting. The reason may be that the height of the sprue is short, and the sequential solidification is not formed during the solidification process of the casting, resulting in the loose structure of the casting, and the quality of the casting will deteriorate accordingly. The average time for double runners is slower than the average time for single runners, which means that the defects produced will be smaller than those produced by single runners. The reason for this may be that the double runner has two sprues, and the solidification sequence is controlled by each sprue, resulting in an isolated cooling sequence of the flange, resulting in a significant change in the hotspots' average time.

From the above results, there is no region with a high overall temperature in the temperature field in the single-runner-round flange pre-filling and double-runner-square flange pre-filling casting schemes. When the double runner-square flange pre-filled type is filled with liquid, the filling time will be shorter, and the temperature distribution and liquid area will be more uniform. The alloy transitions from the liquid phase to the solid phase in the temperature range of 548.5 °C to 651 °C. In the transition zone, both the metal liquid phase and metal solid phase exist, and the temperature change will be gentler than that of a single-phase temperature change [26]. For asymmetrical bindings, the molten metal in the transition zone and the molten metal in a single phase will form an obvious gradient due to factors such as different liquid feeding sequences of the casting. This eventually results in hot spots in areas of the casting that cool slowly. The use of double runners will cause the average time of hotspots to become longer, which is not conducive to the feeding of the cooling shrinkage area by the gating system. Therefore, it is easier to obtain high-quality asymmetric bending castings by using the single runner-round flange pre-filled gating scheme, considering the casting hotspots and the feeding capacity of the gating system.

3.3. Effects of Different Gating Systems on Solidification Process

Different gating systems will have a certain impact on the solidification process of castings. By analyzing the solid phase fraction, cooling rate and shrinkage porosity distribution of different gating systems, the solidification law of asymmetric thin-walled castings by different gating systems is mastered.

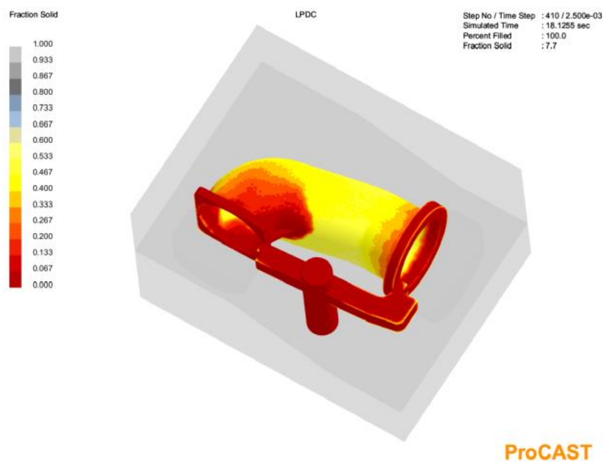
3.3.1. Solid fraction

The solid fraction of castings obtained by different pouring schemes are shown in Figure 9. From the simulation results, due to the existence of thin-walled surfaces, some castings have solidified after the filling is completed.

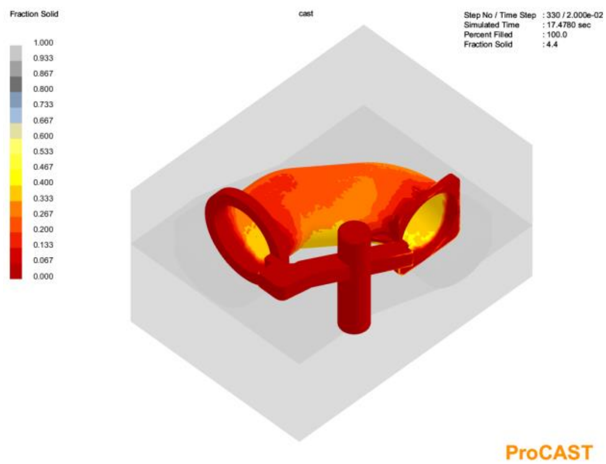
It can be seen from Figure 9-a and Figure 9-b that the overall thin-walled area of the casting is large and the heat dissipation conditions are good. Both casting schemes solidify first at the thin wall and last at the square flange and round flange, and the casting can achieve sequential solidification. However, the flange part of the casting is relatively large, and it is easy to generate hot spots inside the flange, as shown in Figures 8-a and Figure 8-b, which will reduce the solidification rate in this area. In addition, due to the height difference between the casting gate and the top of the casting, the filling time of the thin wall of the cavity will increase. And the castings are asymmetrical parts, and the volume distribution is uneven, which leads to the accelerated solidification rate of the pre-filled castings. In contrast, the double-sprue gating system in Figure 9-c and Figure 9-d gradually solidifies from the lower side of the thin wall from bottom to top, and the liquid phase area of the flange part and the gating system is larger. The thin-walled area does not solidify at the same rate, and defects such as shrinkage cavities and porosity will appear on the thin-walled area.

It can be seen from Figure 9-a and Figure 9-c that the solid phase gradient of the single sprue casting is obvious, and there is no part with a low cooling rate in the thin wall. In the double runner, there is a local area solid rate gradient blurring, and an isolated liquid phase area will appear in this part under the subsequent cooling trend (as shown in Figure 9-e). After the surrounding thin walls are solidified, a feeding channel cannot be provided for them. Also in Figure 9-b and Figure 9-d, it can be seen that the solid phase area of the thin-wall solidification of the double-runner casting is larger, but the gradient of the solid phase rate value converges on the thin wall (as shown in Figure 9-f). In this region there will be a local slowing of the solidification rate and an isolated liquid phase region will appear. This cuts off the feeding channel, creating defects in the thin walls, and ultimately resulting in poor quality thin walls of the casting.

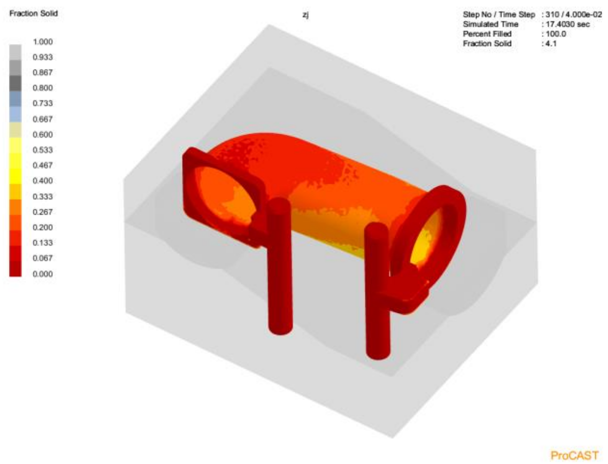
It can be seen from Figure 9-a and Figure 9-d that the liquid phase area of the single runner-round flange pre-filled type is larger, and the solid fraction value of the thin wall is more uniform. The double runner-square flange prefilled type exhibits a stepped solid fraction value because the runners of the double runner are independent. And the length of the sprue is not as long as that of the sprue in Figure 9-c. At this time, the cooling rate of the advanced liquid in the thin wall will be faster than that of the latter liquid. Therefore, after the cavity is filled, the thin wall of the casting near the runner of the advanced liquid solidifies faster.



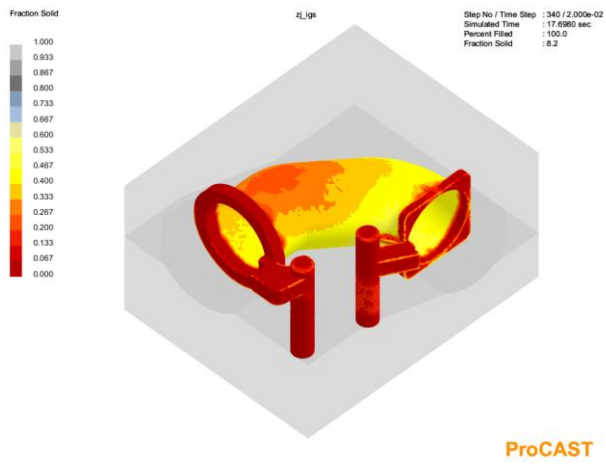
(a) Single runner-round flange pre-filled type



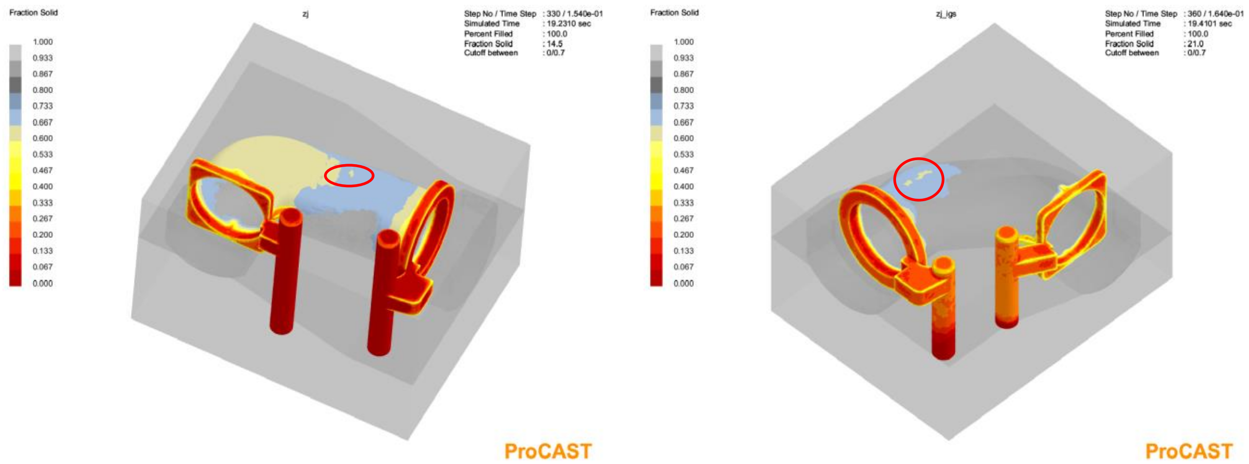
(b) Single runner-square flange pre-filled type



(c) Double runner-round flange pre-filled type



(d) Double runner-square flange pre-filled type



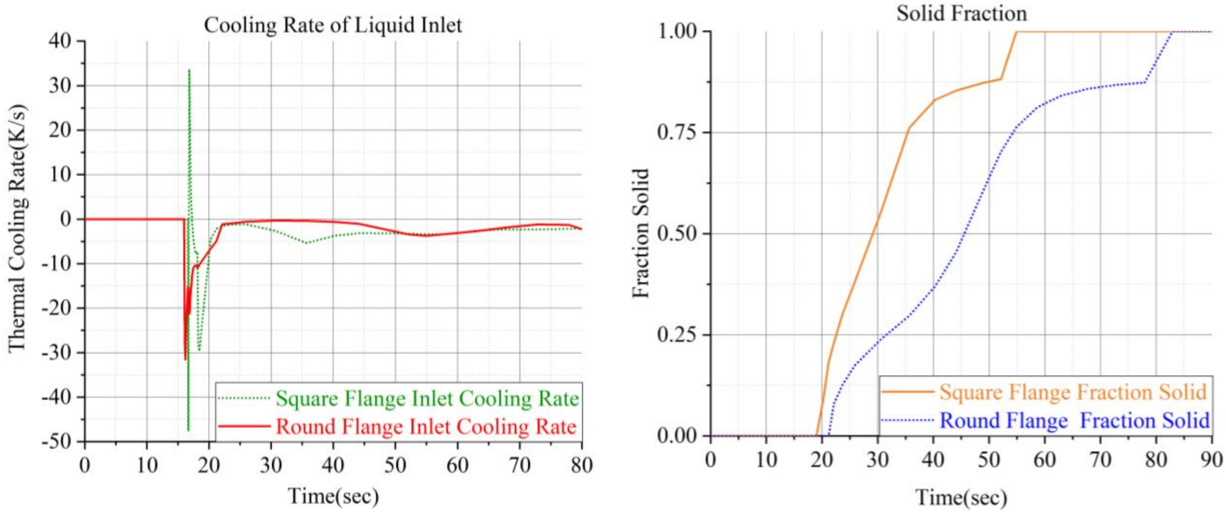
(e) Double runner-round flange prefilled solidification (f) Double runner-square flange prefilled solidification

Fig. 9. Solid fraction of different pouring schemes

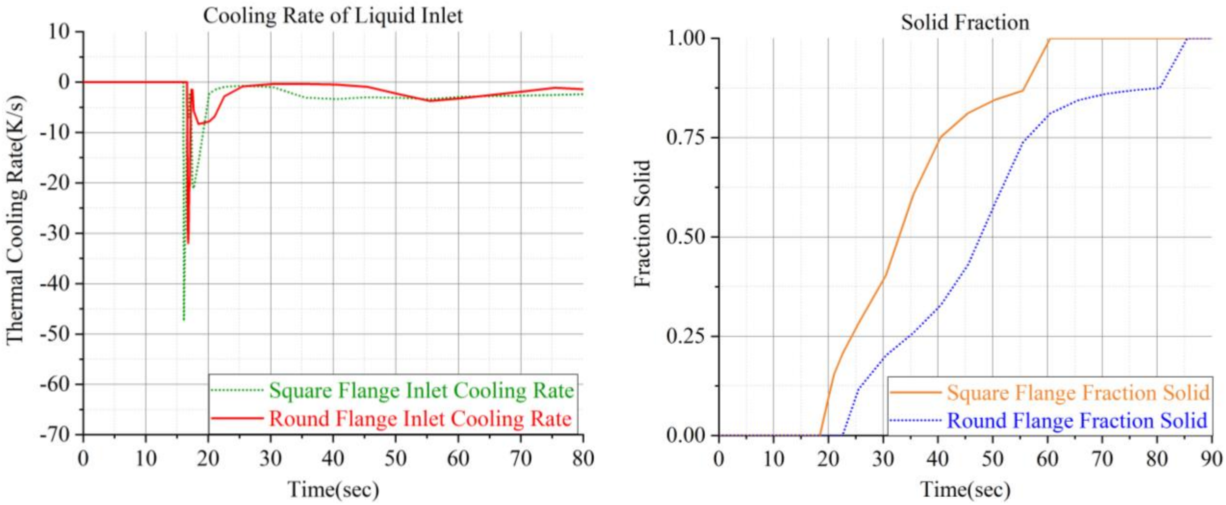
During sequential solidification of the casting, the inlet will solidify after the cavity solidification is complete. Figure 10 shows the cooling rate and solid fraction at the inlet for different pouring schemes. From the simulation results, the solidification time of the liquid inlet of the square flange is shorter than that of the circular flange. This indicates that the volume and thickness of the flange will affect the cooling rate of the casting.

It can be seen from Figure 10-a and Figure 10-b that the cooling rate of the casting and the solid evolution process of the casting will be affected by the different orders of liquid feeding. In the round flange pre-filled type, the solidification interval of the primary and secondary liquid inlets is longer, which is beneficial to the feeding system of the casting system during the cooling and shrinkage process of the casting. When the liquid inlet of the circular flange begins to solidify, the molten metal is cooled at a rate of 0~10K/s, and the cooling process is stable, avoiding the formation of high-temperature cracks and ensuring the compactness of the casting structure. Also in both schemes of Figure 10-c and Figure 10-d with double runners, it can be seen that the difference in the order of liquid injection will lead to differences in the final solidification results of the casting. However, the length of the sprue affects the solidification sequence of the liquid inlet, which in turn affects the solidification sequence of the casting. There is even a situation where the liquid inlet of the circular flange solidifies before the liquid inlet of the square flange. This may be because the sprue is shorter than the top of the casting, and the liquid inlet solidifies before the top of the casting begins to solidify. The solidification time of the liquid inlet of the circular flange is advanced, the feeding channel for the cooling and shrinkage process of the casting is reduced, and the compactness of the casting cannot be guaranteed [27].

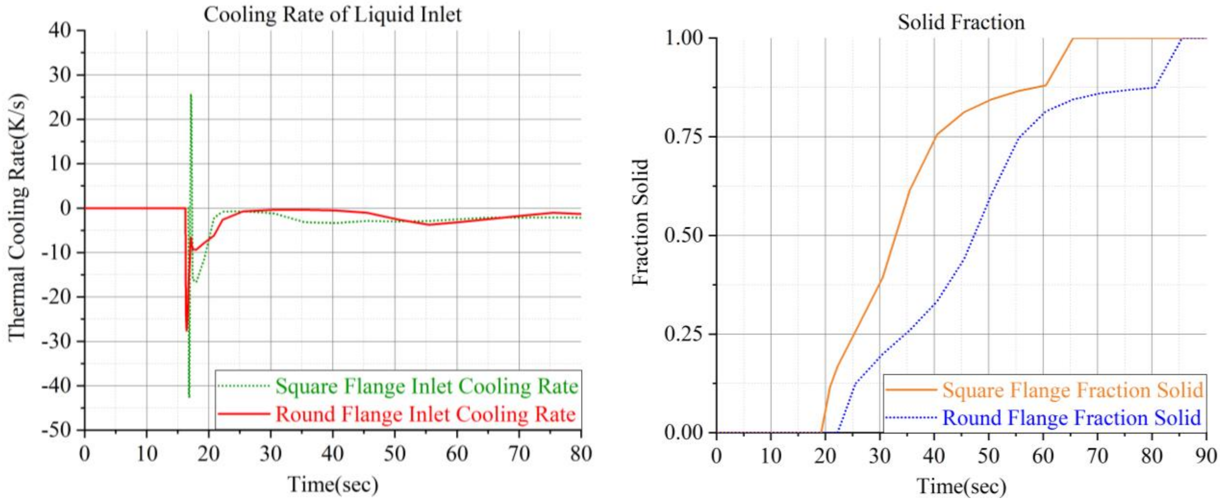
It can be seen from Figure 10-a and Figure 10-c that for the solidification process of the casting, the solidification time of both single and double runners is advanced, and the feeding channel is reduced. Although the cooling rate of the double-sprue circular flange inlet is faster during the filling process, the cooling rate drops to 0 during the pressure-holding stage, and a dense casting structure cannot be formed. At the same time, quality problems such as cracks will occur where the cooling rate is too fast. It can be seen from Figure 10-b and Figure 10-d that the double runner has the same problem as the above, indicating that the use of the double runner gating system will reduce the feeding ability of the casting and affect the grain refinement.



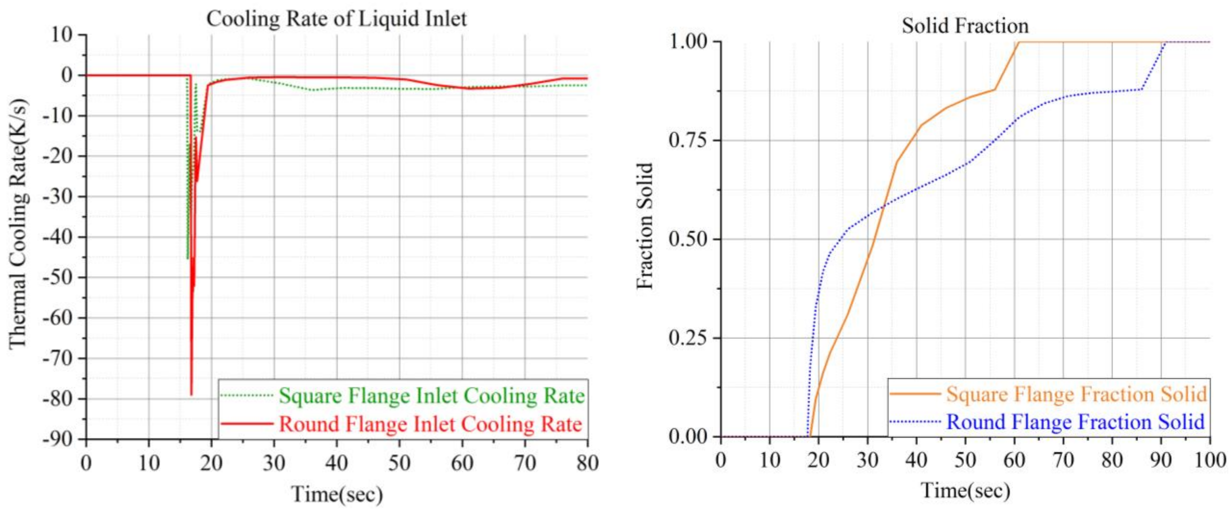
(a) Single runner-round flange pre-filled type



(b) Single runner-square flange pre-filled type



(c) Double runner-round flange pre-filled type



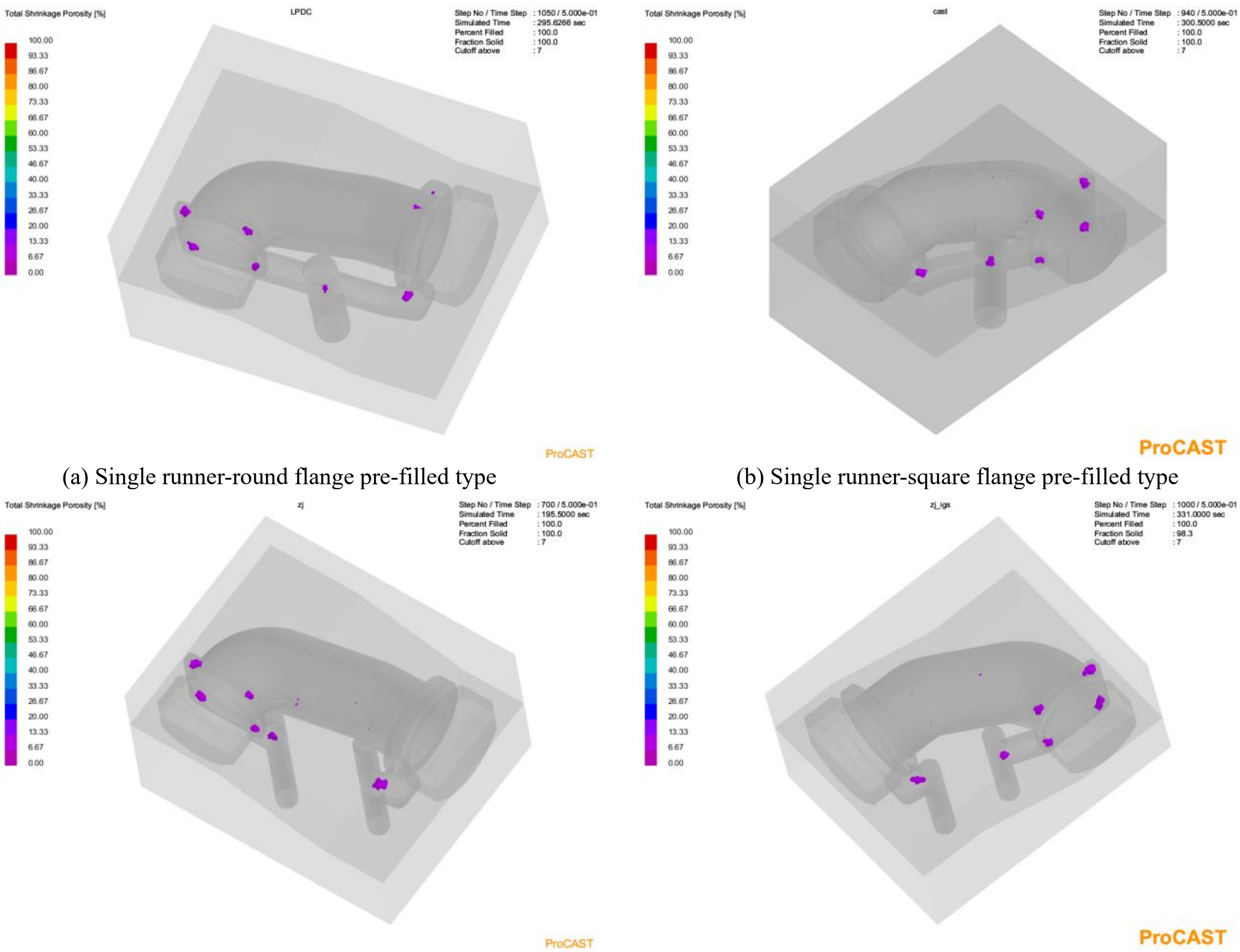
(d) Double runner-square flange pre-filled type

Fig. 10. Cooling rate and solid fraction of liquid inlet

By comparing the solid phase fractions, it is found that both the single runner and the double runner can obtain the casting solidification sequence from bottom to top, thus ensuring the sequential solidification of castings. However, the rate of change of the solid fraction of the casting with time during the solidification process will affect the overall thermal balance of the casting's temperature field and the development trend of the thermal gradient. Conversely, the temperature field affects the feed length between metal dendrites [28], and finally affects the compactness of the casting structure. At the beginning of the solidification of the casting, the solid fraction value of the casting surface is uniform, and there is no isolated liquid phase area. However, during the solidification process of the double runner-square flange pre-filled mold, an isolated liquid phase region is formed on the thin wall of the casting, and the casting will have defects in this region. And the double runner gating system will advance the solidification time of the gate and reduce the feeding channel. The rate of change of solid fraction over time is greater in the single runner-round flange pre-fill type, and the encrustation time of the casting will be significantly advanced. Within the pressure-holding time specified by low-pressure casting, it can be ensured that the casting can avoid the situation of insufficient pouring after the pressure-holding time expires. And the gate cooling rate and solid fraction change can ensure the feeding capacity of the gating system to a greater extent. For asymmetrical bending fittings, under the influence of temperature field and solid phase fraction, high-quality castings can be obtained by adopting the single runner-round flange pre-filled casting scheme. The casting forms a dense structure at the thin wall, which improves the casting quality of the casting.

3.3.2. Shrinkage porosity distribution

Figure 11 shows the shrinkage porosity of the casting obtained by using different pouring schemes. It can be seen from Figure 11-a and Figure 11-b that the shrinkage porosity defects in the casting are distributed at the square flange. And the round flange pre-filled type also produces a small number of defects on the upper part of the circular flange. At the square flange, due to the distribution of thermal spots in both casting methods (as shown in Figure 8-a and Figure 8-b), isolated hotspots are generated here. Finally, defects are generated at the isolated hotspots. It can be seen from Figure 11-c and Figure 11-d that shrinkage porosity defects are generated at the isolated hotspots of the square flange (Figure 8-c and Figure 8-d). At the same time, shrinkage porosity defects appeared in the thin-walled part of the casting. And distributed in the isolated liquid phase region where the solid fraction of the casting appeared.



(a) Single runner-round flange pre-filled type (b) Single runner-square flange pre-filled type

(c) Double runner-round flange pre-filled type (d) Double runner-square flange pre-filled type

Fig. 11. Shrinkage porosity distribution of different pouring schemes

The shrinkage porosity was selected by the software under different pouring methods and the volume was calculated. The results are shown in Table 1. Using numerical simulation software to extract and calculate the volume of shrinkage porosity generated in the casting to obtain the shrinkage porosity existing in the casting. It can be seen from the data in the table that the shrinkage volume (excluding defects in the runner) occupied by the single runner-round flange prefilled type is the smallest, about 2.74cm^3. The proportion is calculated according to the generated shrinkage volume and the total volume of the casting, and the ratio is 0.25% of the entire casting volume, which is also the result of the smallest shrinkage volume among the four pouring schemes. Therefore, it is easier to obtain castings with fewer defects by using the single runner-round flange pre-filled casting method.

Table 1.
Shrinkage porosity volume of different casting methods

Pouring way	Single runner-round flange pre-filled type	Single runner-square flange prefilled type	Double runner-round flange pre-filled type	Double runner-square flange pre-filled type
Shrinkage volume (without runner)	2.74 cm^3	2.90 cm^3	2.93 cm^3	3.35 cm^3
Volume proportion	0.249%	0.259%	0.262%	0.300%

3.4. Results Comparison and Analysis of Four Gating Systems

The filling process and solidification process of the four designed pouring schemes are analyzed. The flow field state, temperature field state, solid phase fraction and shrinkage porosity distribution determine the pros and cons of each gating system, as shown in Table 2.

The comprehensive comparison of casting projects in Table 2 shows that the single runner-round flange pre-filled scheme is the best, the double runner-round flange prefilling scheme is the second, and the square flange prefilling scheme is the worst. The results show that the difference in the pre-filling sequence of the flange and the distance from the second liquid inlet to the top of the casting in the casting structure will affect the quality of the asymmetric bending casting. Using software simulation to determine the single runner-round flange pre-filled casting method can ensure better casting quality. At this time, during the casting process, the filling is stable, and the temperature field distribution is ideal, which is conducive to the formation of a dense structure. The sequential solidification is good, which is beneficial to obtain castings with good performance. The volume of shrinkage defects is the smallest, and thin wall and flange quality is also well.

Table 2.
Comparison and analysis of different gating systems

Pouring way	Flow field state	Temperature field state	Solid fraction	Shrinkage porosity distribution
Single runner-round flange pre-filled type	best	best	best	best
Single runner-square flange prefilled type	better	good	good	good
Double runner-round flange pre-filled type	good	better	good	good
Double runner-square flange pre-filled type	good	good	better	better

4. Practical Casting Test and Analysis of Results

Using the simulation calculation of the part gating system, it is determined that the optimal solution of the gating method is single runner-round flange pre-filling. To verify the feasibility of this scheme, a metal mold and a sand core need to be designed, and an actual casting experiment of asymmetric bending pipe to be verified in a low-pressure casting machine.

4.1. Casting Experiment

4.1.1. Materials used

The alloy material selected for the asymmetric aluminum alloy bending casting is ZL105A, and its composition is shown in Table 3.

Table 3.
Chemical composition of ZL105A

Element name	Si	Cu	Mg	Mn	Zn	Fe	Al
Quality scores /%	5.2	1.3	0.45	0.1	0.1	0.3	based

4.1.2. Casting parameter settings

Combined with parameters such as the size of the part and the height of the liquid riser, the pressure in the casting process in the furnace is set according to Table 4. After the end pressure holding time is over, the castings and metal molds need to be cooled in the air for 310s to obtain asymmetric aluminum alloy bending castings.

Table 4.
Furnace pressure setting table

	Litre part 1	Litre part 2	Litre part 3	Litre part 4
Termination pressure (mbar)	180	500	560	650
Litre time (s)	5	6	8	6
Termination pressure hold time (s)	0	0	0	15

4.1.3. Mold design and manufacture

The numerical simulation results show that the casting method of single runner-circular flange pre-filling was more suitable for asymmetrical bending pipe. According to the selected parting surface and the structural characteristics of the bending parts, the mold is designed as an upper and lower parting, which is composed of upper and lower half-molds and sand cores. Since the casting is an asymmetric thin-walled part, to better form the shape of the casting, the sand core needs to be fixed in the mold, and the grooves at both ends of the mold are designed to place the sand core. The upper and lower molds are designed according to the parting surface of the part, and part of the bending parts and the sand core are brought out by the lower mold, and a part is brought out by the upper mold, which can avoid the deformation during the production of the mold. It can also improve the quality of the outer surface of the casting and shorten the processing cycle of the mold [29, 30]. The casting mold and sand core are shown in Figure 12.

(a) Upper and lower molds and closing mold

(b) Sand core

Fig. 12. Mold and sand core

4.1.4 Practical casting test

The J455 low-pressure casting machine was used for casting (Wuxi Shengda Xinke Machinery Manufacturing Co., Ltd.) and the insulation electric furnace (TCGD3-500-30) is chosen for low-pressure casting (Beijing Taiguang Energy Saving Technology Co., Ltd.). The specific pressure parameter settings are shown in Figure 13. Before the casting test of the casting, it is necessary to paint the inside of the mold to be facilitated remolded. After the mold and sand core are fixed and placed, the mold is preheated, the mold temperature is raised to 250 °C [31], and then the mold filling work is performed. After the instrument starts to work, it will carry out the filling process, pressure maintaining process and cooling process of the casting according to the set pressure and time, and finally, obtain a qualified bending casting.

Fig. 13. Low-pressure casting equipment and actual parameter settings

4.2. Analysis of Casting Results

Figure 14 is the actual forming casting obtained by the single runner-round flange prefilled casting scheme. From the obtained castings, it can be seen that the appearance quality of each surface of the bending castings is good, the reinforcing ribs are well formed, the flange working surface is flat, and the castings are filled with complete molds. Serious defects such as insufficient pouring and macro cracks were not found on the casting surface.

Fig. 14. Results of actual casting test

Figure 15 is a sectional view of the casting along the square flange. It can be seen that the obtained castings have good thin-wall quality, high flange forming degree and no obvious casting defects. This shows that this process scheme is more reasonable.

Fig. 15. The sectional view of the square flange

After that, the experimenter divided the inner flange of the casting and found that there was a small amount of sand sticking in the inner cavity of the casting and a large deviation of the flatness, as shown in Figure 16-a. After analysis, new sand with concentrated particle size distribution and better falling sand can be selected as the sand core, so that castings with better surface quality can be obtained, as shown in Figure 16-b.

(a) Bad quality (b) Good quality

Fig. 16. Sand core affects the surface quality of the inner cavity of the casting

5. Conclusions

The forming process of asymmetrical bending pipe of casting aluminum alloy under different gating systems was analyzed by simulation and experiment, the following research conclusions were obtained:

1. The stepped parting surface can be chosen for the asymmetrical bending parts, which can ensure the mold can be opened smoothly and the stiffener ribs and other positions are also formed smoothly.
2. The cross-flow runner with single runner and round flange can be used for the asymmetrical bending pipe casting part at low pressure. It can ensure the part is filled stably, which is conducive to the sequential solidification of castings, air or slag discharge convenient and shrinkage and other defects are reduced. So, the high quality of castings will be get.
3. The practical casting test verified that a complete asymmetric aluminum alloy bend casting can be prepared by using a single runner-round flange pre-filled type.

Acknowledgments

This research was financially supported by the Industrial Research Projects of Guizhou Province, China (GZ NO.[2015]3004). Moreover, this research was also financially supported by the Guizhou Industry Simulation Design & Innovation Center (QKZYD NO.[2016]4006). This research was also supported by Doctoral Research Foundation of Guizhou Normal University (2017). In the end, thanks the company of Guizhou Huaheng Machinery Manufacturing Co., Ltd. for their helping.

References

[1] Zhang, M. & Chen, L.F. (2011). A Review of the Development of Aluminum Alloy Casting Process in High-voltage Switchgear. *High voltage apparatus.* 47(4), 75-83. https://doi.org/10.13296/j.1001-1609.hva.2011.04.016.

[2] Jiang, Z. (2012). Numerical Simulation of Die-casting Process of Aluminum Alloy End Cap. *Precision Forming Engineering.* 4(1), 30-33.

[3] Zheng, X.Q., Xie, S.K., Yi, R.X. & Guo, X.Y. (2016). Low Pressure Casting Technology: Development History, Research Status and Future Trend. *Material Guide.* 30(07), 74-80+85. https://doi.org/10.11896/j.issn.1005-023X.2016.07.013.

[4] Qian, Y.J., Cheng, Z.H. & Yu, H. (2012). Application of Numerical Simulation in Casting. *Precision Forming Engineering.* 4(4), 39-43.

[5] Li, L.Y., Wang, X., Sun, K.S., Gao, C. & Zhang, B.R. (2022). Effects of Sand Casting and Low Pressure Casting on the Microstructure and Mechanical Properties of Ultra Long Aluminum Alloy Box Dyeing. *Foundry Technology.* 43(03), 197-202. https://doi.org/10.16410/j.issn1000-8365.2022.03.007.

[6] Zhang, X.Y & Yang X.L. (2010). Discussion on Technological Progress of Metal Mold. *Casting Foundry Technology.* 31(11), 1524-1526.

[7] Yan, S.Q., Lin, Y.X., Zheng, K.K. & Fan, Y.P. (2019). Research Progress in Coatings for Metal Mold. *Casting Hot working process.* 48(03), 11-14. https://doi.org/10.14158/j.cnki.1001-3814.2019.03.003.

[8] Zhang, J.Y. (2021). Special Casting Process Method. *World Nonferrous Metals.* (9), 141-142.

[9] Xu, X.L., Qiao, X.H., Yang, Y., Mou, Y.H. (2022). Casting Process Optimization and Application of Large Runner Water Jet Propulsion Parts. In Chongqing Foundry Annual Conference. Chongqing, China. https://doi.org/10.26914/c.cnkihy.2022.008747.

[10] Liang, Y.D., Liu, Q.Z., Hao, C.S., Lu, D.B., Hao, Y., Jiang, L., & Li, S.J. (2022). Example Analysis of Sand Mold Low Pressure Casting Process Design for Aluminum Alloy Complex Thin-walled Parts. *China Foundry Equipment and Technology.* 57(3), 87-90. https://doi.org/10.3969/j.issn.1006-9658.2022.03.020.

[11] Zhang, L.Q. & Wang, R.J. (2012). Design of LPDC Process for Thin-walled Casting Based on Numerical Simulation. *Applied Mechanics and Materials.* 217-219, 1786-1790. https://doi.org/10.4028/www.scientific.net/AMM.217-219.1786.

[12] Zhang, L.Q. & Wang, R.J. (2012). Numerical Simulation of LPDC Process for Thin-walled Aluminum Alloy. *Advanced Materials Research.* 538-541, 474-478. https://doi.org/10.4028/www.scientific.net/AMR.538-541.474.

[13] Liu, J.D., Zou, X.H., Zou, X.D. & Chai, S.L. (2022). Setting of Low Pressure Casting Pressure Curve for Aluminum Alloy Cylinder Block Castings. *Metalworking (hot working).* 6, 111-113.

[14] Liu, J.G., Zhang, Y.M, Fang, X.G, Wang, D.F, Yang, Y.W. & Wu, Z.R. (2020). Design and Optimization of Low Pressure Casting Process for Multi-function Display Console. *Casting.* 69(12), 1325-1330.

[15] Horr, A.M., Angermeier, C. & Harrison, A. (2014). Full Through Process Simulation for Low Pressure Die Casting – from Casting to Design. *Materials Science Forum.* 794-796, 118-123. https://doi.org/10.4028/www.scientific.net/MSF.794-796.118.

[16] Dhisale, M., Vasavada, J. & Tewari, A. (2022). An Approach to Optimize Cooling Channel Parameters of Low Pressure Die Casting Process for Reducing Shrinkage Porosity in Aluminium Alloy Wheels. *Materials Today: Proceedings.* 62(6), 3189-3196. https://doi.org/10.1016/j.matpr.2022.03.478.

[17] Li, A., Wu, M. (2003). Practical Manual of Casting Process Design Technology and Production Quality Control, Golden Publishing House.

[18] Liang, M.J. (2004). Research on CAD Technology of Aluminum Alloy Low Pressure Casting Process [D], North China Institute of Technology.

[19] Gao, X.Y. (1997). A Cubic Equation Method for Calculating Riser Size and Its Application. *Foundry Technology.* (04), 7-10.

[20] Dong, X.Q., Wang, D. & Wang, C.Z. (2003). Theory and Practice of Low Pressure and Differential Pressure Casting,

China Machine Press.

[21] Dojka, R., Jezierski, J. & Campbell, J. (2018). Optimized Gating System for Steel Castings. *Journal of Materials Engineering and Performance.* 27(10), 5152-5163. https://doi.org/10.1007/s11665-018-3497-1.

[22] Dojka, R., Jezierski, J. & Tiedje, N.S. (2019). Geometric Form of Gating System Elements and Its Influence on the Initial Filling Phase. *Journal of Materials Engineering and Performance.* 28(7), 3922-3928. https://doi.org/10.1007/s11665-019-03973-9.

[23] Dojka, R., Jezierski, J. & Szucki, M. (2022). The Importance of the Geometry of the Down Sprue in the Gravity Casting Process. *Materials.* 15(14), 4937, 1-31. https://www.mdpi.com/1996-1944/15/14/4937.

[24] Zhang, F., Kang, Y.L., Yang, L.Q. & Ding, R.H. (2010). The Influence of Pouring Temperature on the Cooling Law of Alloy Melt and Semi-solid Structure. *Journal of Beijing University of Science and Technology.* 32(11), 1453-1458. doi:10.13374/j.issn1001-053x.2010.11.014.

[25] Qin, T. & Xu, N.B. (2012). The Influence of Pouring Temperature on Rotor Quality Was Explored by ProCAST. *Modern Cast Iron.* 32(03), 74-77. https://doi.org/10.3969/j.issn.1003-8345.2012.03.014.

[26] Zheng, Q., Xiao, Y., Zhang, T., Zhu, P., Ma, W. & Liu, J. (2020). Numerical Simulation of Latent Heat of Solidification for Low Pressure Casting of Aluminum Alloy Wheels. *Metals.* 10(8), 1-12. https://doi: 10.3390/met10081024.

[27] Vijayaram, T.R., Sulaiman, S., Hamouda, A. & Ahmad, M. (2006). Numerical Simulation of Casting Solidification in Permanent Metallic Molds. *Journal of materials processing technology.* 178(1-3), 29-33. https://doi: 10.1016/j.jmatprotec.2005.09.025.

[28] Thompson, S., Cockcroft, S. & Wells, M. (2004). Advanced Light Metals Casting Development: Solidification of Aluminium Alloy A356. *Materials Science and Technology.* 20(2), 194-200. https://doi:10.1179/026708304225011199.

[29] Jiang, L., Cheng, J.M., Li, S.J., Lu, D.B., Sun, Xi.L., Liang, Y.D., & Liu, N. (2022). Case Study of Die Design for Aaluminum Alloy Castings. *China Foundry Equipment and Technology.* 57(3), 13-15. https://doi.org/10.3969/j.issn.1006-9658.2022.03.002.

[30] Jiang, L., Cheng, J.M., Li, S.J., Sun, X.L., Zhao. N.N., Yu, C. & Liu, N. (2022). Design of Metal Mold for Oil Separator of Aluminum Alloy Castings. *China Foundry Equipment and Technology.* 57(2), 92-94. https://doi.org/10.3969/j.issn.1006-9658.2022.02.015.

[31] Zhang, Z., Wang, P.P., Chen, H.S., Qian, Q.H., Xu, G.B. & Dong, W. (2016). Study on Low Pressure Metal Mold Casting Process of CRH380A Case Cover. *Casting equipment and process.* 2, 11-13. https://doi.org/10.16666/j.cnki.issn1004-6178.2016.02.005.