ARCHIVES
of
FOUNDRY ENGINEERING

DOI: 10.24425/122507

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

ISSN (2299-2944)
Volume 18
Issue 2/2018

84 – 94

15/2

Simulation and Casting Process of Aluminum Alloy Multi-Way Valve Body with Various Gating Systems

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Received 06.11.2017; accepted in revised form 30.03.2018

Abstract

In order to study the effects of various gating systems on the casting of a complex aluminum alloyed multi-way valve body, both software simulation analysis and optimization were carried out. Following, the aluminum alloyed multi-way valve body was cast to check the pouring of the aluminum alloy valve body. The computer simulation results demonstrated that compared to the single side casting mode, the casting method of both sides of the gating system would reduce the filling of the external gas, while the air contact time would be lower. Adversely, due to the pouring on both sides, the melt cannot reach at the same time, leading to the liquid metal speed into the cavity to differ, which affected the liquid metal filling stability. The riser unreasonable setting led to the solidification time extension, resulting in a high amount of casting defects during solidification. Also, both gating systems led the entire casting inconsequential solidification. To overcome the latter problems, a straight gate was set at the middle pouring and the horizontal gate diversion occurred on both sides of pouring, which could provide better casting results for the aluminum alloyed multi-valve body.

Keywords: Casting, Aluminum alloy, Valve body, Gating system, Simulation

1. Introduction

The integral hydraulic multi-valve is a key component of the highest technical level for construction machinery [1, 2]. The manufacture of an integral multi-way valve body involves the material, the molding, the heat treatment and other issues. Any issue of the valve body will eventually affect the final performance [3]. Currently, most integral multi-valves are made from ductile iron. But it have a big problem: the temperature of casting is high (about 1300 ^{o}C), the core sand would adhere on the inside flows. It would made the hydraulic oil system pollution. So, the aluminum alloy material is choose to make the multi-valve body. A high performance aluminum alloy body can bear the high pressure for hydraulic system. The aluminum alloy can clean the sand inside the oil flow easily, which can make the hydraulic oil system be cleaning. With the continuous development in the aerospace and automotive industries, the high-performance aluminum alloy research and development for the production of high-performance key components is essential. Due to the complicated internal flow channel of the multi-way valve body, it is proven significantly difficult to design the core directly, to carry out the pouring experiments. Also, the casting simulation software could view the defect locations and propose the solution, which is not required for the actual poured castings [4, 5, 6]. A simulation was carried out for the filling process of the integral multi-way valve body. The forming of the valve body was observed under different pouring systems, to predict the possible defects and to finally modify the entire casting process. Through simulations and optimizations, the best casting process could be obtained for the high strength aluminum alloyed multi-valve body preparation.

2. Analysis of Casting Process and Pouring System Design

2.1. Valve body modeling and process analysis

Due to the multi-valve body comprising complex internal runners, it is usually produced through casting. In order to facilitate the simulation of the molding, a digital model of the valve should be first established, as presented in Figure 1.

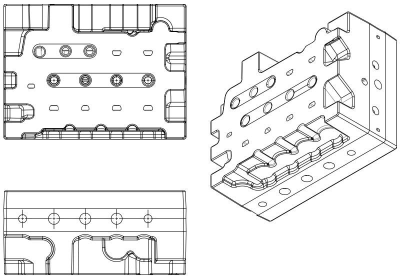


Fig. 1. Model of multi-valve

Since the internal runners of the valve body are complicated, many runners cannot be produced by mechanical tools. The runner should be made with sand core and on the mold. Subsequently to the liquid alloy molding, the core sand will drop through vibration. Consequently, an internal cavity will be formed. For easy casting, the entire mold of sand both internally and externally should be considered. The body cavity is formed through core molding and the main body is also formed through internal sand molding. The pouring system and the riser are formed with an outer mold. These internal and external molds could be easily assembled. The overall sand molding is presented in Figure 2.

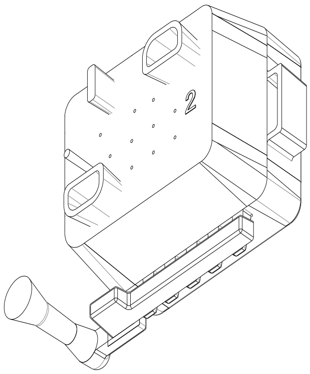


Fig. 2. Model of overall sand molding

2.2. Design of pouring system

2.2.1. Overall design of pouring system

The quality of the pouring system will directly affect the molding quality of the casting product. Many factors that affect the pouring system exist, such as the gating system type and the pouring system location. According to the characteristics of the valve body, many thinner and irregular runners exist inside the product, making suitable for the close -open -close gating system. This meant that the sprue to the runner path will be closed and the outer runner to the inner runner path was open. The gating system can ensure the effective slag removal and the melt stability in the casting. It contains both the close and open advantages of the runner, while its structure is presented in Figure3.

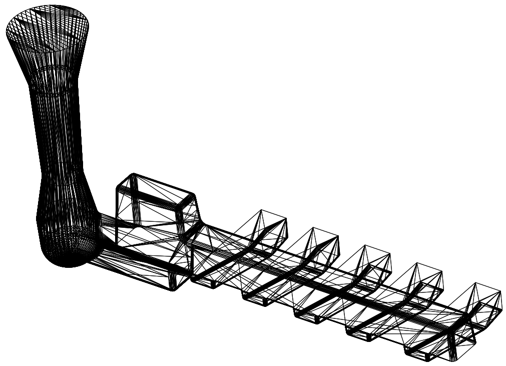


Fig. 3. Pouring system

Figure 3 presents that the casting system of the valve body is designed as a long straight runner through the upper and lower molds. Also, the connection between the outer runner and the inner runner is a slag. The molten metal flows from the bottom of the sprue to the runner. Following, the melt enters the five gates through the slag. It would allow the pouring stream to enter the mold cavity slowly and reduce the air entrainment.

2.2.2. Relevant sizes calculation of pouring system

Firstly, the minimum cross-sectional of flow (A_{smin}) should be calculated [7]:

$$A_{smni} = \frac{G_L}{Kt\sqrt{H_p}} \tag{1}$$

A_{smin}-cm^2.

where, G_L is the weight of the casting. The riser weighed twice the weight of the valve body; consequently, G_L=1.8G_C (G_C is the valve body weight). According to volume and density of this product, its weight was approximately 35kg and G_C=35kg. Also, G_L=1.8 x 35=63kg.

K is the flow factor generally taking the values of 0.04-0.07 for aluminum alloys. It will take the upper limit when the mold resistance would be high. Therefore, the valve of this casting had K=0.07.

t is the pouring time. According to $t= s'\sqrt[3]{G_L}$ and s' is the empirical coefficient [8]. The average thickness of the valve body was 15mm, set as s'=3.6. Therefore, the pouring time was calculated: t=3.6x3.98=14.32s.

H_p is the average static pressure head (unit: centimeters). Since the intermediate injection mode was selected:

$$H_p=H_0-0.125C \quad (2)$$

where, H_0 is the depth of gating and C is the casting height.

Therefore, H_p =24-0.125x16.6=21.925cm.
Consequently, A_{smin}=63/ (0.07 x 14.32 x 4.638) =13.55cm^2.

Secondly, the cross-sectional area ratios of the casting system components were required to be given. For the pouring system, the sprue to the runner path was selected in the closed mode and for the outer runner to the inner runner path the open mode was selected. This could improve the liquid metal stability in the cavity during pouring. Moreover, the oxidation slag would be blocked when it was being poured. According to the minimum cross-sectional area of the latter calculation and according to the common cross-section ratio of the aluminum alloy casting system components [8], which could take the ratio, the produced relationship was F_{sprue}: F_{runner}: F_{inner}= 1: 3.5: 2.5. This cross section ratio would ensure both smoothness of pouring and efficient blocking of the slags.

3. Simulation results analysis

The simulation process mainly included the product model import into the simulation software, the pre-processing completion of the model, the grid division, the parameter calculations and finally the simulation calculation of the product. This research was mainly focused on the product filling effect under various gating systems. Moreover, the turbulent flow state, the pressure distribution and the filling temperature field of the casting were analyzed.

3.1. Filling process analysis

3.1.1. Gas state analysis of filling under various gating systems

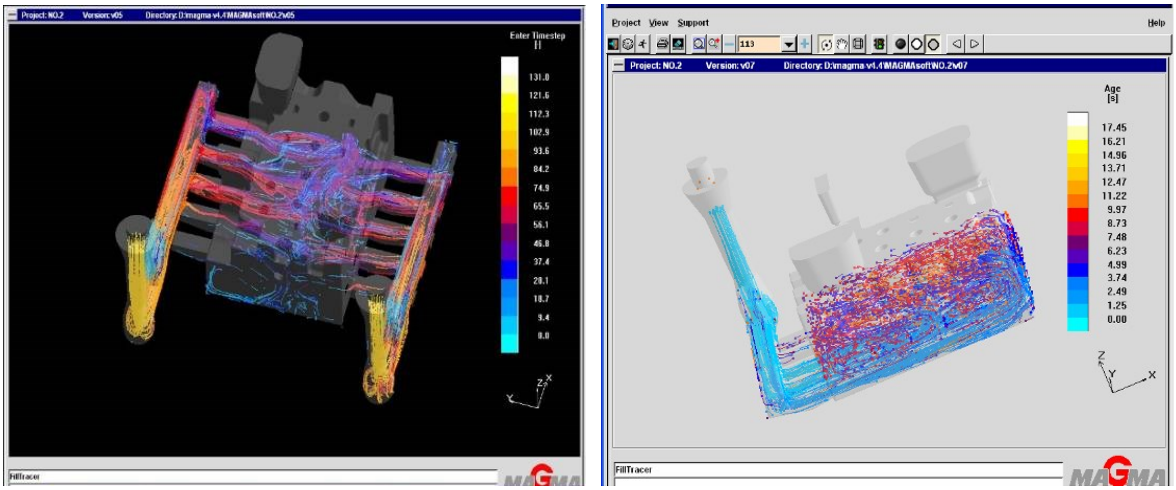
Figure 4 presents the tracer particle status of various gating systems. It presents that both melt streams met in the product center and produced strong turbulent flows at both sides of the gating system. The single side gating system would produce a smooth backflow, due to the melt flow front being blocked by the mold cavity. Through the backflow, a certain volume of air could be formed, mold set some risers in the end of backflow, which could rapidly discharge the gas. The air volume impact for the qualities of the castings could be reduced.

Figure 5 presents the air contact time of the twin side gating system and the single side gating system. If the time of contact with the air was longer, the castings would more likely oxidize [9].

From the results presents in Figure 5, the air contact time of the twin gating system was lower than the single side gating system, specially the upper surface area of the castings. It was due to the more slowly metal flow in the single gate system. Following the bottle of the casting being covered by the melt, the cavity air would be warm and concentrated at the upper region of the cavity and the slips. The air would penetrate or contract with the casting. Furthermore, when the temperature was low, the air would be trapped in the casting, which would lead to loose product surface. In any case, the sectional views of the various gating systems shows were slightly different.

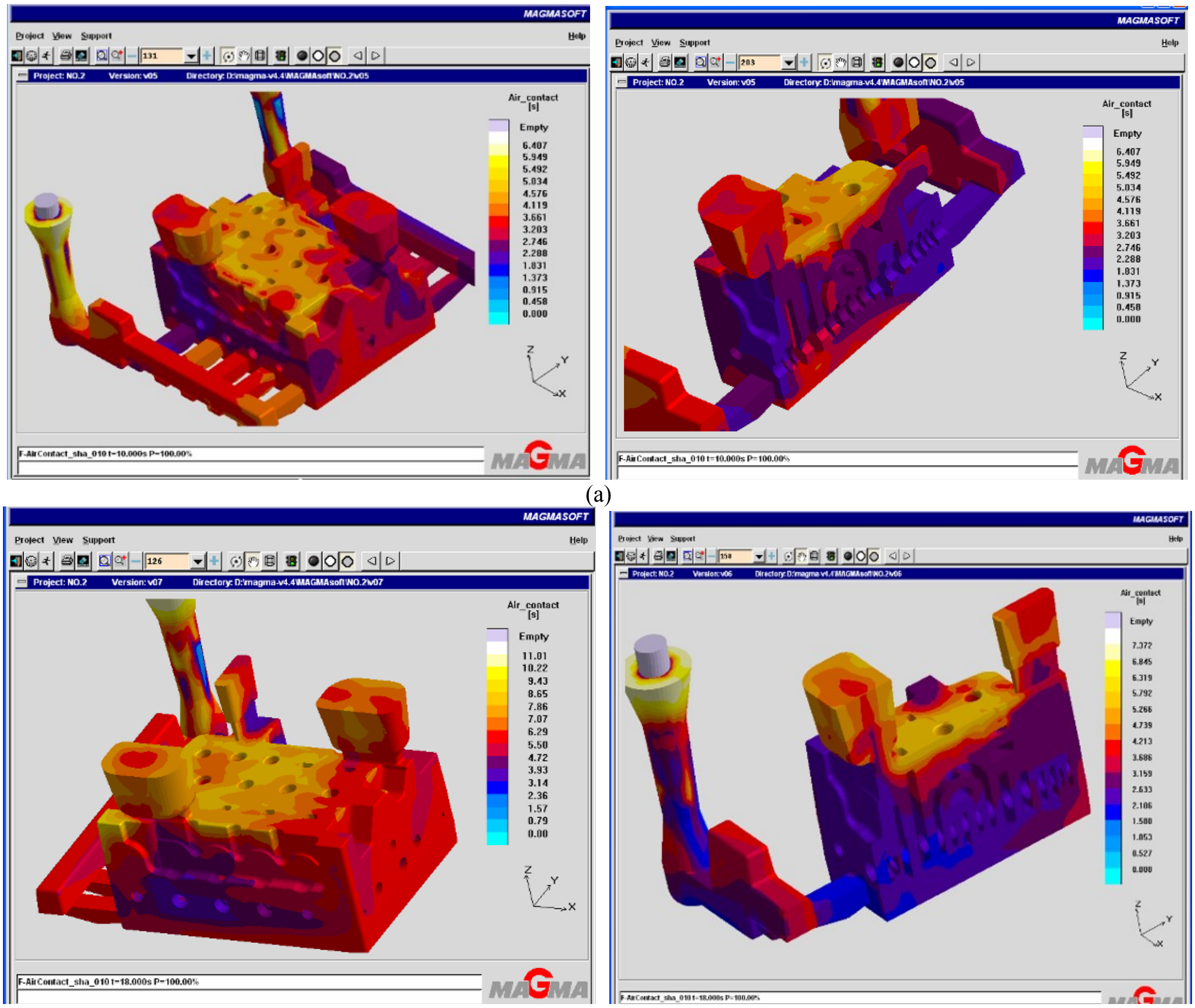
For the twin gating system, the simultaneous pouring of the melt would lead to excess air entrapment in the cavity. Following the two melt fronts convergence, a stronger turbulence resulted in the gas pressure increase. This increased the kinetic energy of the gas, which increased the gas penetration to the various regions of the product cavities. This status increased the air contact times of the core region (center of valve body). It is the core region was a key area for the valve body parts. Consequently, the air contact times increased the risk for body defects. When a single side gating system was used, its internal air contact was mainly concentrated in the metal liquid scouring area and at a higher area of the wall. This was because the melt flow was relatively slow and the molten metal could coat the core. Consequently, the air was eliminated from the cores and the contact time in the core surface was low. The flow scour zone substituted the air during the metal flow injection, resulting in an increased contact time in this zone. The thickness area was due to the riser cooling and contraction, resulting in the regional gas not being discharged. This area would increase the exposure time to the air.

Subsequently, this casting should increase the exhaust amount in the gating system. Moreover, the size of the riser was also required to be increased, for the oxide slag to be discharged through the riser as high as possible to reduce the defects of the castings.



(a) (b)

Fig. 4. Tracer particle status of various gating systems: a) Twin side gating system; b) Single side gating system



(a)

(b)

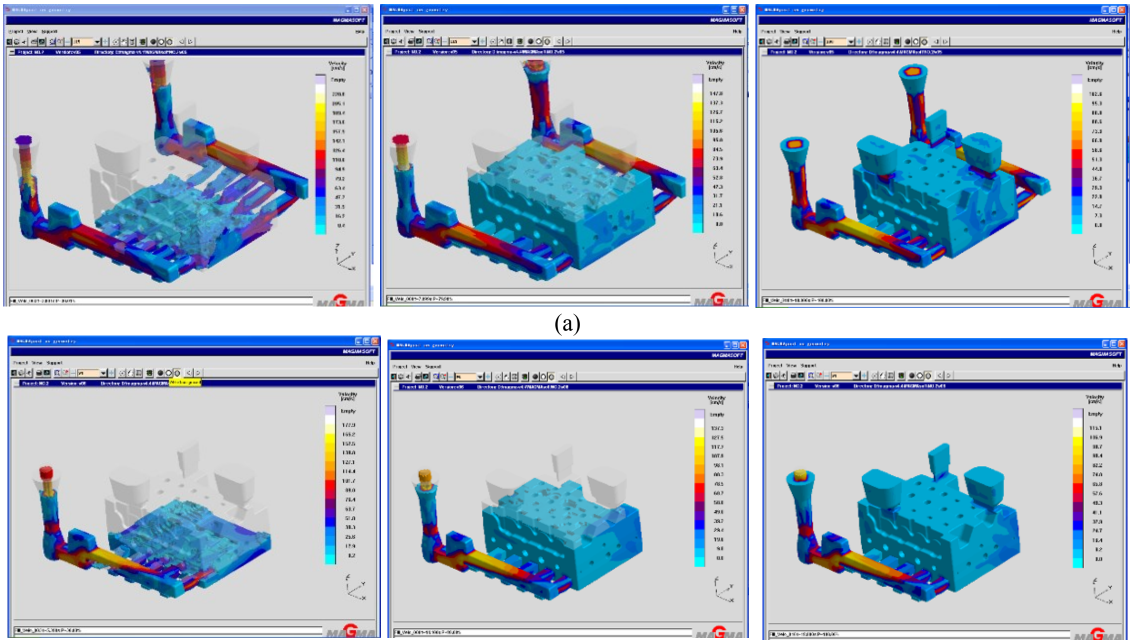
Fig. 5. Air contact times of various gating systems: a) Twin gating system; b) Single side gating system

3.1.2. Analysis of filling speed under various gating systems

Figure 6 presents the filling speed distribution status under various gating systems. Through comparison of Figure 6 (a) and (b), the filling speed of the twin gating system was significantly higher than the single side gating system. For the closed filling rate, the liquid metal frontier area had higher velocity fluctuation for the twin gating system. Since collision and vibration occurred by both liquid metal flows, the speed fluctuations were intensified. On the other hand, the filling speed of the single gating system was significantly smoother. Only in the area of filling the inlet and the backflow had higher filling speed, whereas the other filling areas would be relatively stable.

For the riser area, the twin gating system demonstrated a quite high flow rate (exceeding 60 cm / s), while the single side gating system was significantly lower (just approximately 33 cm / s). This occurred because the cavity pressure of the twin gating system increased, which squeezed the metal to the upper riser. In contrast, the riser sectional area was low and resulted in the injection effect of the metal in this region. It reached high speeds in this zone. For this issue, the optimization mold should increase the riser size and its cross section.

Following, different areas had different filling speed distributions. For the twin gating system, the speed was higher. This was because the twin gating system would pour the liquid melt flow into the cavity at the same time, which would lead to temperature increase of the entire casting and the cores. This phenomenon promoted the liquid metal fluidity and also intensified the speed fluctuation.


(a)

(b)

Fig.6. Filling speeds of various gating systems: a) Twin gating system; b) Single side gating system

3.2. Solidification Process

For the process of solidification, it was necessary to analyze the solidification relative parameters. Similarly to the temperature and the cooling rate, the hotspots under various pouring systems were required to be checked. Also, the porosity, the hot tearing and other defects during solidification were required to be simulated, to ensure the quality of the valve casting under different pouring systems.

3.2.1. Solidification temperature and defects analysis

From Figure 7 it could be observed that the final solidification area of the castings of both casting systems occurred at the end of the cross-flow. A position shows the area of the both side castings. After the melt passing by the slag and being into cross-flow, the melt flow section was lower-sized. This would result in the melt flow pressure to increase, also leading to the cross-flow melt and the molten metal speeds acceleration at the bottom of the cross-flow. Therefore, the gating could produce the highest metal flow at the end of the cross-flow. A high amount of molten metal existed in the cavity from this gating, which led to the highest temperature of solidification and the solidification time was also long.

These hotspots would lead to more defects for the valve body. In the actual production, it is necessary to improve the process according to the structure of the casting and reduce the occurrence of casting defects [10]. The hotspot distribution of the half solidification is presented in Figure 8. These hotspots were focused on the gating of the cross-flow end. Not only the gating position, but additional hotspots existed in the valve body section for the single gating system.

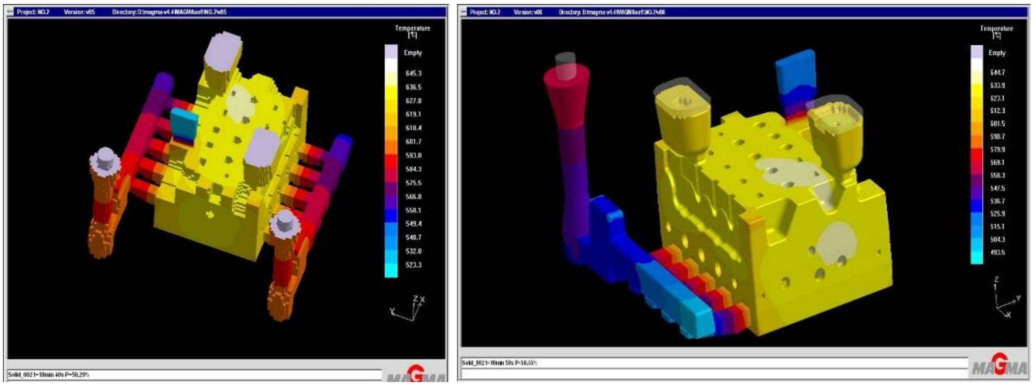
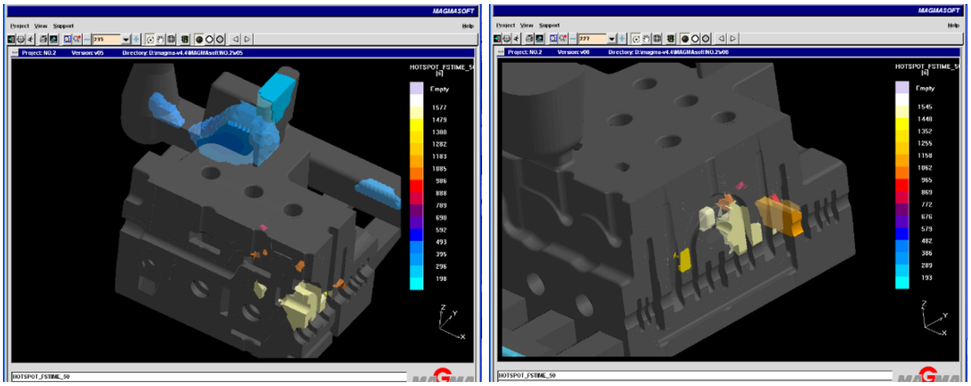


Fig. 7. Temperatures of various gating systems

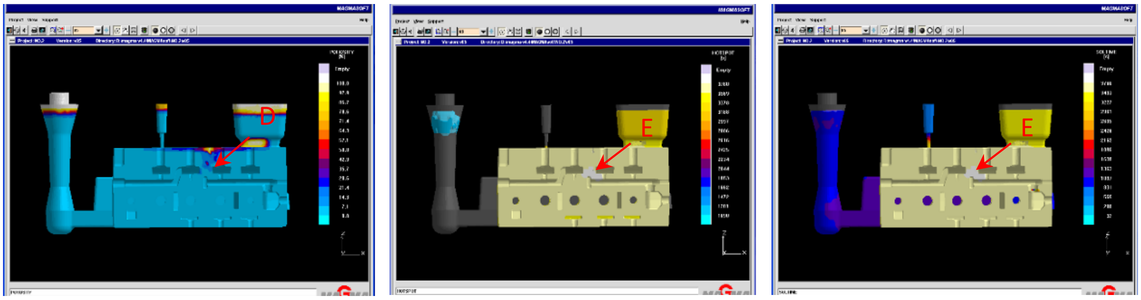


(a) (b)

Fig. 8. Hotspots of different gating systems: a) Twin gating system; b) Single side gating system

As presented in Figure 9, the zone of hotspots and the final solidification distribution of the casting were at the E position above the core, but the porosity of the casting was at the D zone. The depth of porosity was approximately 10-15mm, while also certain loose areas of approximately 50mm existed below the top surface. A certain offset existed between the two center positions of the final solidification and the porosity zone. This difference probably resulted by the kinetics of the metal liquid replenishment: The liquid metal always flowed from the high potential area to the low potential area, producing porosity [11]. The molten metal was continuously converged to the valve body cavity and consequently spread to other areas. The final solidification area was the E zone. For higher temperatures, this region required longer solidification time. After the surrounding metal cooling, the solidification latent heat of crystallization could continuously diffuse towards the periphery, especially upwards. This heat caused the alloy to remelt, but it could be replenished. Therefore, a low potential region porosity occurred.

Therefore, in order to prevent the occurrence of the aforementioned process, it was necessary to increase the riser size around the final cooling zone, especially at the upper region of the final cooling position, to prevent the occurrence of casting defects.



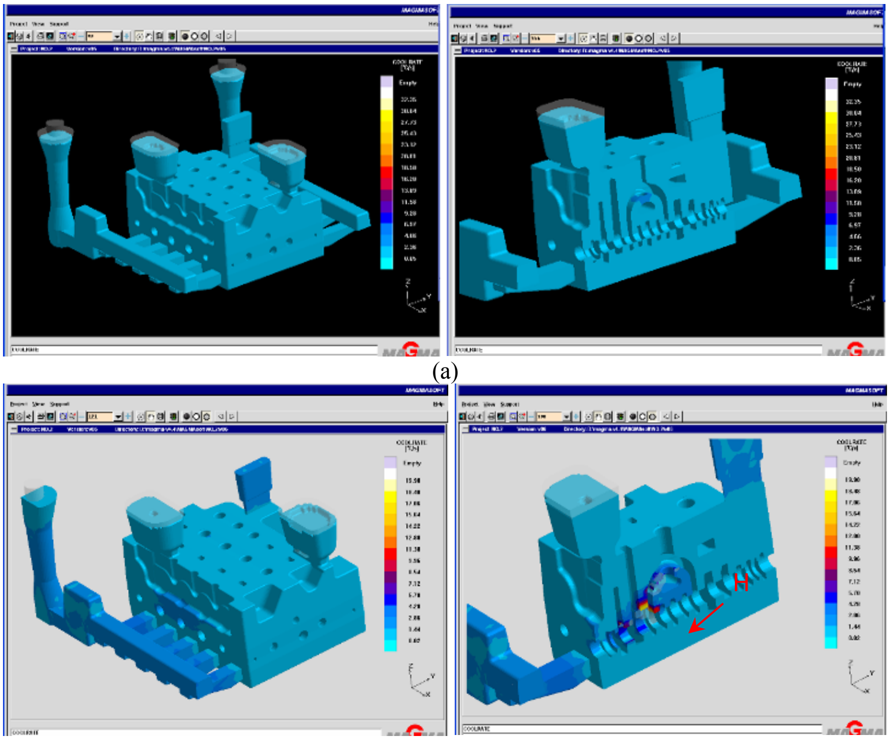
(a) (b) (c)

Fig. 9. Distribution of shrinkage and hotspots: a) Porosity; b) Hotspots; c) Time of solidification

3.2.2. Solidification speed and defects analysis

Figure 10 presents the cooling rate of the casting solidifications under various casting systems. It could be observed from the solidification cooling rate of the twin gating system that the overall cooling rate of the casting was more consistent, while the cooling rate was higher only in the part where the core was placed in the valve body, as presented in Fig. 10 (right part). (a). The cooling rate of a single side gating system was significantly different from the twin gating system: firstly, a faster cooling rate occurred above the two ingates at the middle of the casting surface, as presented in Fig. 10 (left part). (a). Secondly, additional high cooling rate areas appeared at different parts of the single side gating system. It was concentrated at the valve hole positions (core placement area). A high cooling rate existed at the H position of Fig. 10. (b) and its value was 20 °C/s.

The simulation results demonstrated that the high cooling rate of the valve body mainly occurred at the area where the core was placed. Especially in the area where the core was compounded, it was easier to produce a significantly high cooling rate. This was mainly due to the temperature, at which, the core would absorbed the metal melt during casting, especially when the assembly core contained air. These gases absorbed heat during casting and exacerbated the temperature drop at these areas. An excessive cooling rate can easily lead to porosity defects. Therefore, during the actual pouring of the products, it was necessary to preheat the cores for a sufficient time to ensure the temperature uniformity of the entire cores and reduce the solidification speed decrease.



(a)

(b)

Fig. 10. Cooling rate of casting solidifications of various gating systems: a) Twin gating system; b) Single side gating system

4. Optimization designed

4.1. Gating system optimization

Problems existed for the aforementioned gating systems. The twin gating system is prone to flow hedging, which leads to high-sized splashed in the valve body cavity. Especially, the body center is a key zone, which would lead to defects. In addition, the internal flow apparently increased in both side gating systems, resulting in the air contact time extension, which led the products to be severely oxidized. Finally, this twin gating inconvenienced for the actual melt casting. For the single side gating system, its flow was gentle, but the turbulence could not be avoided afar from the gating position. Also, this valve body was a high-sized casting and the slow flow would lead to the front flow easy cooling, which would form the defects.

To solve these problems, the gating system of the valve body should be optimized. The improved and optimized casting system is presented in Figure 11. A single gate dual-flow way was adopted to inject the liquid from the middle. Slag bags were placed at both ends of the inner flow to ensure that the melts enter the cavity simultaneously and the alloy flow to be smooth and even. The simulation result is presented in Figure 12. It was presented that the liquid metal system was gentler, while the metal flow eddy current was lower. This also resulted in short air contact time and the zone size to be reduced.

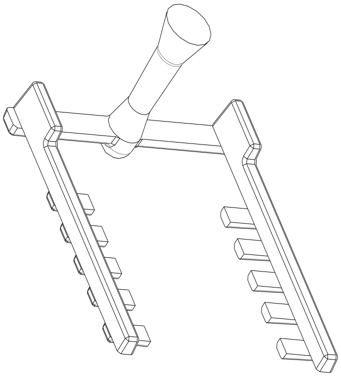


Fig. 11. Optimized gating system

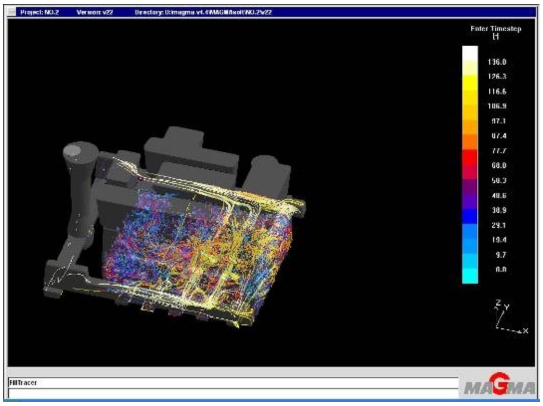


Fig. 12. Turbulence of new gating system

4.2. Valve body defects optimization

The simulation results demonstrated that severe shrinkage occurred at the middle and top of the casting. This was because the riser settings were unsuitable. This zone was thick and the riser could not present sufficient filling. Also, the distribution of the riser was not reasonable. To end this phenomenon, the location and size of the risers were required to be modified to ensure that the metal melt could be re-positioned in all positions. Consequently, the new riser was designed, as presented in Figure 13. The risers settings were high for the top metal melt pressure to be applied to the cores of the body castings. The vent size around the valve body was increased to ensure that the air inside the cavity could be promptly discharged.

The defects of the modified product are presented in Figure14. It could be observed that the main shrinkage cavities and shrinkage defects were concentrated at the riser area. Also, the inside of the body did not present apparent defects. Its filling rate also demonstrated that this casting scheme could provide an improved solidification effect.

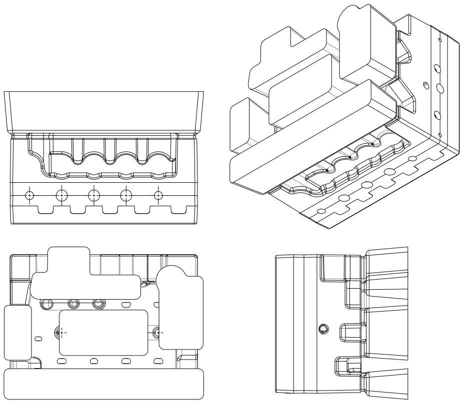


Fig. 13. Modified riser of valve body

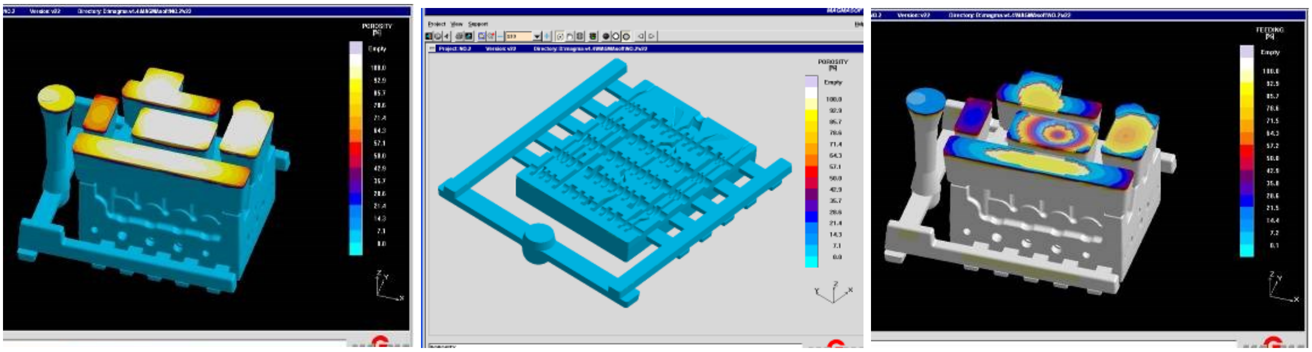


Fig. 14. Defects and filling rate optimization

4.3. Casting solidification temperature

The optimization gating system led the solidification temperature distribution to be more legitimate and the result is presented in Figure 15. The solidification temperature was sequentially solidified. The center area could be effectively supplemented to prevent the occurrence of a severe shrinkage hole or loose defects. The temperature gradient of the casting was more uniform. Only a slight temperature drop at the core area of the valve occurred, which required the core to be heated during the actual casting.

The optimized simulation results demonstrated that the modified gating system could provide a satisfactory filling flow field and the ideal solidification field.

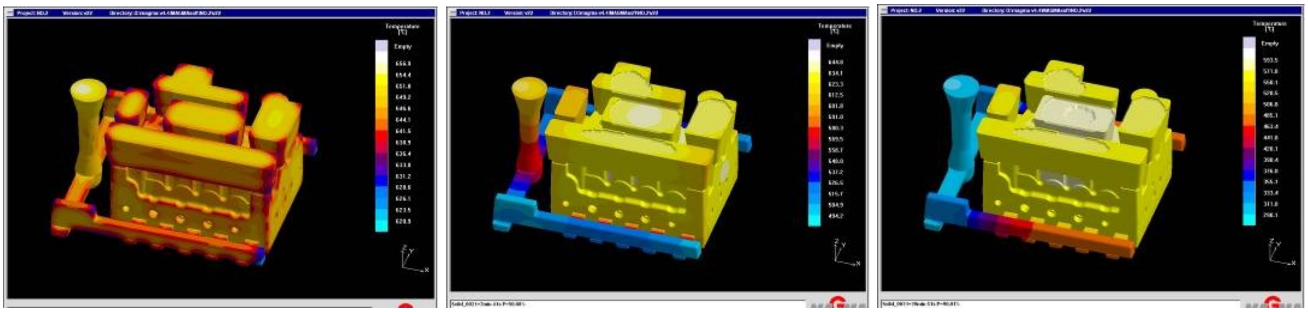


Fig.15. Solidification temperature of modified gating system

5. Experimental results and analysis

5.1. Single side gating system pouring

As presented in Figure 16, the castings of the single side gating system were produced. From the entire casting, the riser basically met the requirements. No significant defects appeared. Adversely, many flashings occurred within the pouring runner, indicating that the mold clamping was not sufficiently precise.

Following the risers cutting, significant shrinkage occurred at the upper area of the valve body. In addition, a low amount of shrinkage occurred laterally close to the upper area. The results of the casting coincided with the simulation results: the shrinkage occurred at the central area and severe defects occurred on the surface.


Fig. 15. Casting of single side gating system

The body was cut through wire sawing, while the positions of the internal flow channel defects in the castings were in good agreement with the shrinkage positions of the simulation, as presented in the G zone of Figure 16.

The inside flow was smooth for the aluminum valve body. The entire flow channel area did not require special cleaning sand except for a certain amount of shrinkage to be overcome.

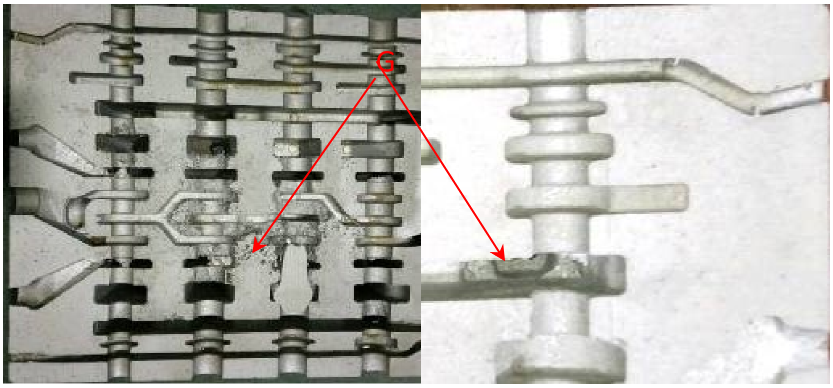
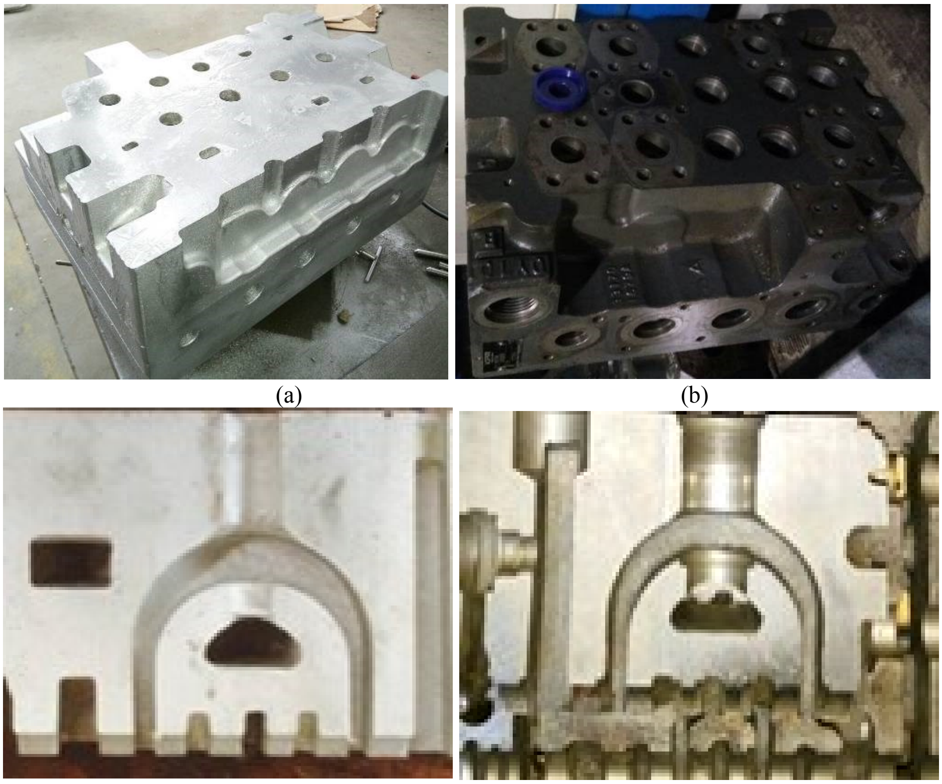


Fig. 16. Cutting section of aluminum alloy valve body

5.2 Optimized casting product

As presented in Figure 17, the aluminum alloy body surface was smooth and thick. The defects on the surface were basically ruled out subsequently to optimization. It is close to the cast iron valve body.

Following the optimized aluminum alloy body and the cast iron valve body cutting, the flow channel size and the former structure was similar to the iron valve body structure. Also, it was very smooth and clean. This demonstrated that through the optimized aluminum valve body casting utilization, the valve body forming could basically be achieved for the large-scale trial production of the aluminum alloyed valve body.



(a) (b)

(c) (d)

Fig. 17. Comparison of aluminum alloy and iron body: a) Aluminum alloy body; b) Iron valve body; c) Partial area of Aluminum alloy body; d) Partial area of iron valve body

6. Conclusions

From the aforementioned analysis, the following conclusions were drawn:

1) The differences in metal flow conditions were the main factors that contributed to the effects of various gating systems on the filling. The twin gating systems provided faster filling times and less temperature drops, due to faster pour rates, but additional turbulence and increased entrapment of air into the system during filling. The single side gating system was more stable for filling, but easy to oxidize. Consequently, for the multi-valve body, its core zone was the key part and its molding should reduce the filling time, being more stable.
2) The single or the twin gating system could not guarantee the sequential solidification of the valve body. This would also cause defects of the valve body at the core or on the surface. This could result in core strength and surface quality decrease of the valve body.
3) The optimized gating system was based on double gates, which led the flow within the cavity to be gentler. Also, this gating system would lead the melt to both sides of the cavity to be balanced, which guaranteed the simultaneous injection to the cavity of both flows. This system was suitable for this casting and ensured the internal area quality of the aluminum alloyed multi-valve body. The optimized aluminum multi-valve body casting could reach the cast iron optimization level and its internal flow channel was cleaner.

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 Science and Technology Cooperation Plan, Guizhou, China (LH No. [2016]7222) and the Guizhou Province Innovation Center for Industry 4.0 Simulation and Design (QKZYD No. [2016]4006). This research was also financially supported by the Doctoral Research Foundation of Guizhou Normal University (2017).

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