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Application of transparent casting moulds prepared by additive manufacturing technology in hydraulic simulation

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Abstract: Hydraulic simulation is one of the critical methods to research the filling mechanism of molten metal in the casting process. However, it only performs on test pieces with relatively simple structures due to the limitation of the preparation method. In this study, the method of photocuring additive manufacturing was used to prepare the complex casting mould from transparent photosensitive resin. The pouring test was carried out under different centrifugal conditions, and the filling process of the gating system, support bars and other positions in the vertical direction was recorded and analyzed. The experimental results show that the internal liquid level and the filling process of the test piece prepared by this method can be observed clearly. The angle between the liquid surface and the horizontal plane in the test piece gradually increases as the centrifugal rotational speed increases, which means the filling process is carried out from outside to inside at high rotational speed. The velocity of the fluid entering the runner increases with the increase of rotational speed, but the filling speeds is less affected by the centrifugal speed at other positions. The liquid flow is continuous and stable during the forward filling process, without splashing or interruption of liquid droplets.

Keywords: additive manufacturing; centrifugal casting; investment casting; hydraulic simulation; transparent mould

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1 Introduction

In the centrifugal casting process, the filling capacity is the most essential performance of fluid and has a great relationship with the casting performance. The excellent filling ability has a significant impact on the floating and removal of impurities. It is also conducive to the feeding and shrinking of the solidification process, avoiding shrinkage porosity, insufficient pouring, and other defects in the casting [1-4]. Thus, it is of great significance to explore the filling mechanism of molten metal in a centrifugal environment. However, the filling in the centrifugal casting process is usually conducted in a vacuum environment with opaque high-speed rotation. It is challenging to observe the flow of the molten metal in the mould. Therefore, numerical and physical simulations have become the two most commonly used methods to study the casting filling process [5-7].

Numerical simulation technology uses the combination of computer simulation technology and casting process technology to study the filling process of the fluid so as to predict the possible defects through the simulation results [8-14]. It allows estimating the flow characteristics at various conditions and different gating systems. Analyzing through numerical simulation and then verifying in small batch production can provide solutions for the actual process and shorten the production cost caused by trial and error. However, since the fluidity of the metal melt in actual centrifugal casting is affected by many factors, it is not easy to obtain comprehensive and accurate boundary condition

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parameters and experimental data, resulting in low accuracy in the numerical simulation [1, 15].

Physical simulation simulates the primary laws of the actual process by using the principle of similarity based on satisfying similar basic conditions such as geometric, motion, and dynamic similarity [16-22]. Summarizing the general laws in the model and then extending it to a series of practical phenomena similar to the model can provide more reliable reference data for actual production. Compared with actual experiments, physical simulation experiments are easier to control, lower cost, and can be used for more comprehensive research. It can also solve complex processes that are difficult to handle in numerical calculations, so it is an important method to study complex problems. Further, the accuracy of the simulation can be improved through the mutual verification of experimental data obtained by physical simulation and numerical simulation [15]. The hydraulic simulation of filling process is an important method to study the filling law of molten metal. It has good matching properties and is favoured by many scholars worldwide.

Keerthi et al. [23] used transparent water and oil with various viscosities to study the influence of different process parameters on the flow morphology. Li et al. [24] used a combination of hydrodynamic simulation and theoretical analysis to analyze the flow morphology qualitatively. They systematically explained the influence of flow morphology on the formation of casting defects during the filling process of the molten metal. Wang et al. [25] used the hydraulic simulation method to study the factors that affect the delaying time of the rising liquid surface in low-pressure casting. Sui et al. [26] studied the influence of rotation speed on cross-section, filling speed, and filling amount in an approximately two-dimensional transparent model. At present, transparent plexiglass is often used to splice and make a cavity convenient for observing the filling process in hydraulic simulations. Due to the limitation of the preparation method, the existing hydraulic simulations are only performed on test pieces with relatively simple structures.

In summary, scholars have made relevant studies on the filling process of centrifugal casting metal melt by hydraulic simulation. However, limited by the existing model preparation and observation methods, the existing studies primarily focus on the horizontal filling process of fluid in the test piece with simple structure instead of the overall filling process of the test piece with complex structures. In response to this problem, this research combines additive manufacturing technology with hydraulic simulation. The additive manufacturing process was used to prepare different gating systems and test pieces similar to the casing structure using transparent photosensitive resin, so as to effectively observe the filling process of the fluid in the vertical direction of the cavity under the conditions of different rotation speeds.

2 Mould preparation and experimental procedure

The transparent photosensitive resin (standard resin, Esun Industrial Co., Ltd.) was used as the raw material for mould printing. Photosensitive resins are usually composed of crosslinking agents, dispersants, and initiators, among which monomers and crosslinking agents are the main components of the resin system. After receiving certain energy and a specific wavelength of light, the resin will transform from liquid to solid. The additive manufacturing process of photosensitive resin is relatively mature at present. The upward digital light processing (DLP) technology was employed, and the equipment structure (Autocera-L, Beijing Ten Dimensions Technology Co., Ltd.) is shown in Fig. 1. Compared with other forming methods, the DLP has higher forming accuracy, faster forming speed, and better surface quality of the model [27]. When printing starts, the forming platform is first lowered to the lowest position, and the curing thickness of each layer is controlled by the distance between the forming table and the bottom of the material box. The DLP machine located at the bottom of the equipment controls the UV light to irradiate where the slurry needs to be cured based on the imported digital model. After the exposure is completed, the forming platform raises and the scraper moves to recoat the material, then the forming platform moves down again for exposure. The curing process is continuously repeated to fabricate the moulds layer-by-layer. Finally, remove the uncured resin in the cavity with alcohol in time. Spraying varnish on the mould's surface can effectively improve the transparency of the mould.

The two moulds shown in Fig. 2 are designed with different filling and gating systems. The arrow shows the flow direction of the fluid in the cavity. The size of the plate-type cavity is 50 mm×30 mm×4 mm. The distance between the right side of the plate and the sprue (also the rotation axis during centrifugation) of the two systems is equal. It is easy to observe the filling process through the resin mould. The gating system in Fig. 2(a) is located on the inside of the mould, and the fluid fills the plate from inside to outside. This filling sequence is defined as forward filling. It should be noted that the columns at the bottom of the mould only play a supporting role and do not provide the filling function. The gating system in Fig. 2(b) extends to the outside of the plate, and the liquid will flow to the outermost and then fill the plate from outside to inside. This filling

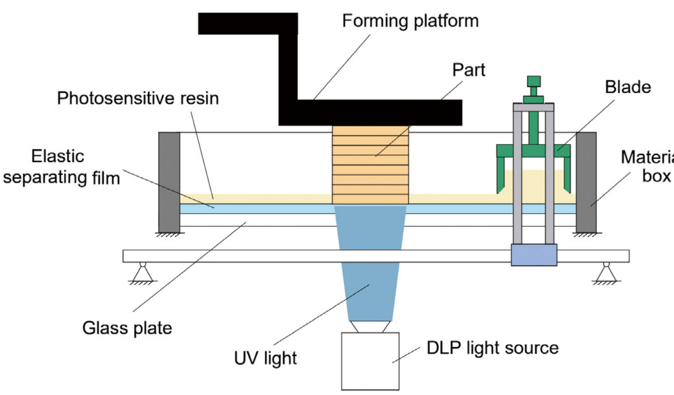

Fig. 1: Schematic diagram of DLP forming equipment structure

sequence is defined as reverse filling. The inner runners are numbered as shown in Fig. 2. The actual printed mould is shown in Fig. 3. Seven vent holes are evenly opened on the top of the mould to ensure the smooth filling of the liquid flow in the cavity (plate).

As shown in Fig. 4, a centrifugal device with adjustable speed was used to realize the centrifugal casting function. At the same time, a small photography device (HERO9, GoPro, Inc.) was fixed on the centrifugal plate, which can realize the shooting of the entire filling process by rotating with the test mould. The photography device can be chosen between various resolutions and shooting frames. In this work, the device was set to shoot 60 frames per second at a resolution of 3840×2160 to obtain better image quality. At the same time, water-soluble blue pigment was used to dye the liquid so that the filling process can be better observed. The rotational speed used in actual production is about 100 to 140 rpm. Referring to this value, the rotational speeds were set to 0 rpm, 40 rpm, 80 rpm, and 120 rpm. The actual speeds were measured as 0 rpm, 42 rpm, 82 rpm, and 122 rpm in the experiment. The beaker containing the solution was placed about 20 mm above the pouring cup at the beginning of each experiment. After the rotation started, the beaker was placed at the same height and poured the solution into the pouring cup slowly to ensure the initial fluid velocity was consistent. The filling process of the two test moulds at four rotational speeds was photographed. The video of the filling process was analyzed frame by frame in the video processing software.

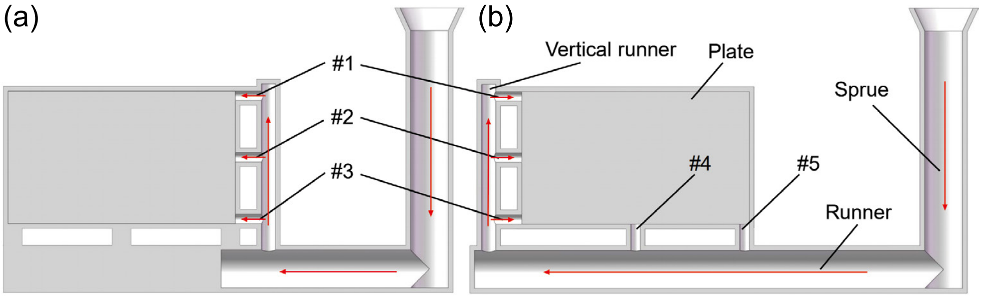

Fig. 2: Schematic diagrams of forward (a) and reverse (b) filling gating system

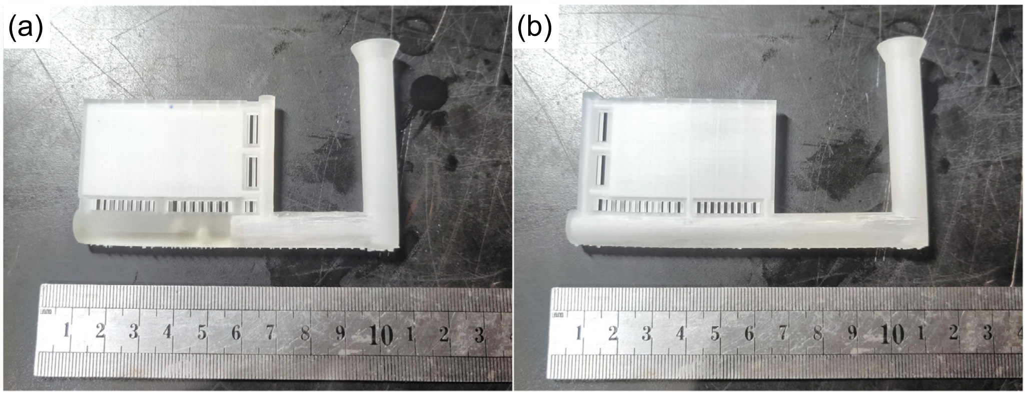

Fig. 3: Moulds prepared by DLP with forward (a) and reverse (b) filling and gating system

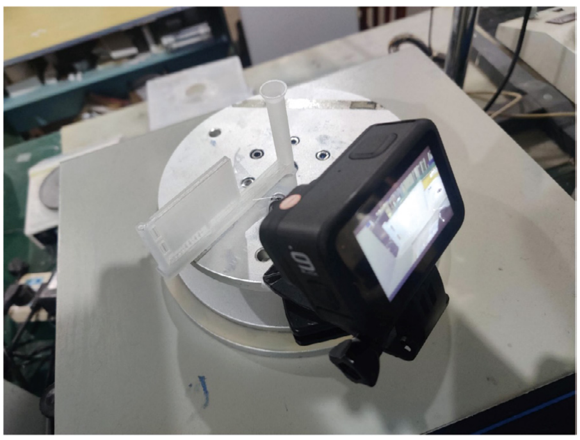

Fig. 4: Centrifugal turntable and camera equipment

3 Results and discussion

3.1 Influence of rotational speed on filling sequence in reverse filling process

Figure 5 shows the reverse filling process at 0 rpm. It can be seen from the figure that when the rotational speed is 0, part of the liquid will enter the horizontal runner at first after the initial fluid reaches the bottom of the sprue. Afterwards, the liquid gradually fills the entire runner from the inside to the outside at a slow and steady speed under the action of hydraulic pressure, as shown in Fig. 5(b). After the runner is filled with liquid, the fluid will fill the outermost vertical runner and the plate simultaneously as shown in Figs. 5(c)–(d). The fluid flows into the plate through the bottom inner runners No. 3, No. 4, and No. 5, and fills the entire plate horizontally from bottom to top, as shown in Figs. 5(c)–(f). Since there is no vent hole on the top of the vertical runner, the liquid level in the vertical runner is lower than that in the plate due to the influence of gas backpressure.

Figures 6–8 show the reverse filling process when the centrifugal speed is 42, 82, and 122 rpm, respectively. Under the action of centrifugal force, the liquid will quickly flow to the farthest end of the horizontal runner after reaching the bottom of the sprue, then fill the runner from the outside to the inside. After the liquid has filled most of the runner, it flows into the plate simultaneously through the bottom inner runners No. 3, No. 4, and No. 5, as shown in Fig. 6(c). Although there is a certain angle between the liquid level in the plate and the horizontal plane, the filling process of the plate is still completed from bottom to top, as shown in Figs. 6(d)–(f). The filling sequence changes significantly at a higher rotation speed. Under the action of a large centrifugal force, the liquid flows into the farthest end of the horizontal runner firstly and then fills the horizontal runner, the vertical runner and the plate simultaneously, as shown in Fig. 7(d) and Fig. 8(d). Therefore, the liquid flows into the plate from the remote inner runners No. 1, No. 2, and No. 3, and the time of the flow to reach the No. 4 and No. 5 inner runners is significantly later than that of gravity filling. The liquid level in the mould is at a larger angle with the horizontal plane, and the filling sequence is changed to from outside to inside, instead of from bottom to top, as shown in Figs. 7(d)–(f) and Figs. 8(d)–(f).

3.2 Influence of rotational speed on filling speed in reverse filling process

The filling speed of the liquid flow was calculated by counting the distance between the liquid front in the two pictures and the frame number of the pictures in the video processing software. The four filling processes of entering the runner, filling the runner, entering the plate, and filling the plate were selected to measure the filling speed. Figure 9 shows the filling speed of reverse filling at different rotational speeds. It can be seen from the data that the filling speed in the plate gradually decreases from a larger value to a relatively stable level as the filling process progresses. The filling speed of the liquid as it enters the runner increases significantly as the rotational speed increases, and the filling speed when filling the runner under centrifugal conditions is slightly higher than that under gravity conditions. However, there is little difference in the filling speed of the liquid entering the plate and filling the plate under centrifugal and gravity conditions.

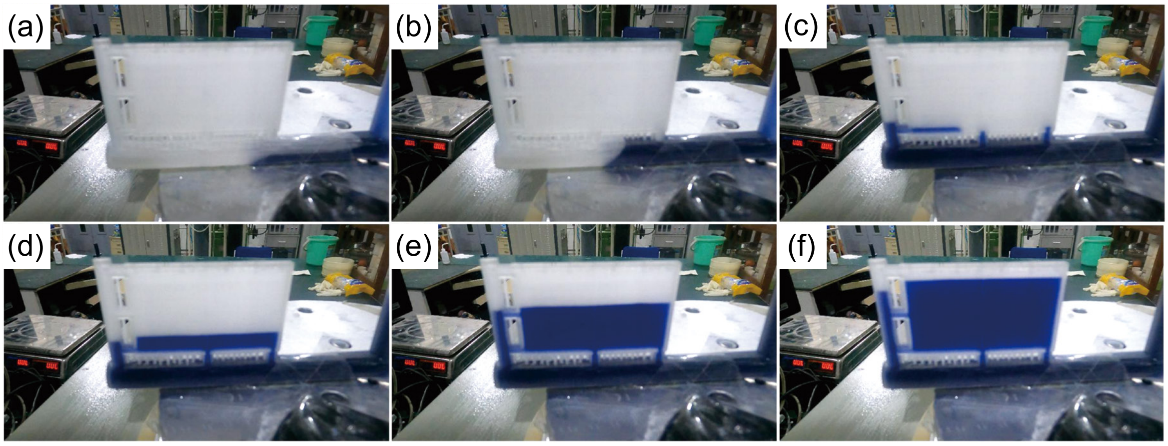

Fig. 5: Reverse filling process under 0 rpm, when the fluid enters the runner (a), fills the runner (b), enters the plate (c), and fills the plate (d)–(f)

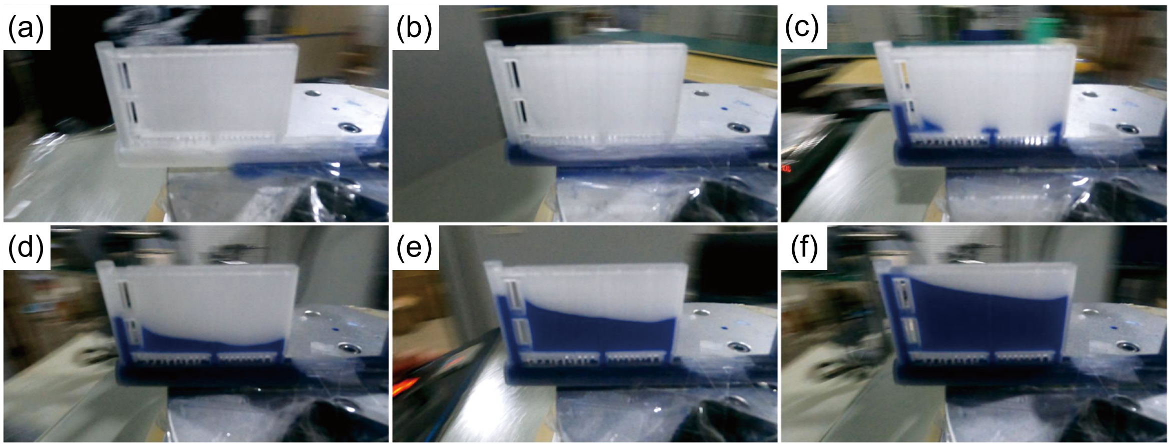

Fig. 6: Reverse filling process under 42 rpm, when the fluid enters the runner (a), fills the runner (b), enters the plate (c), and fills the plate (d)–(f)

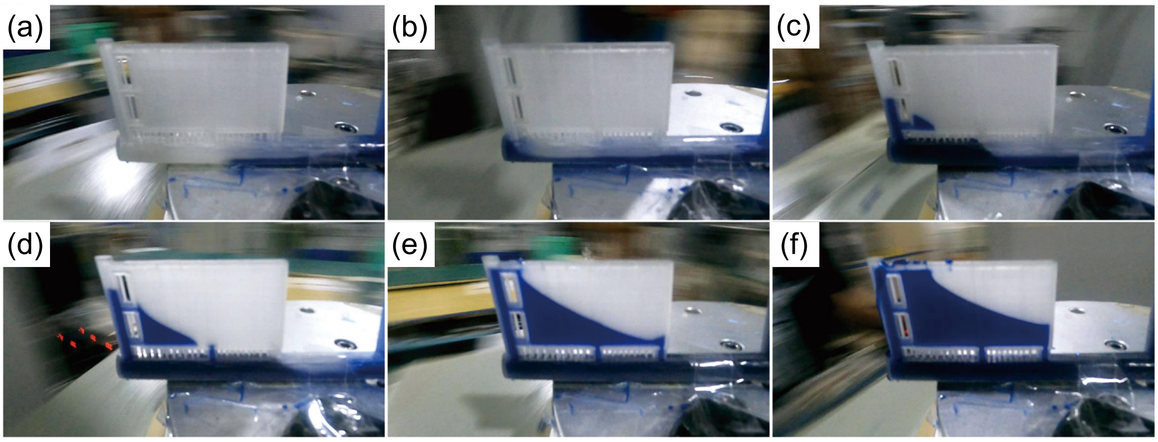

Fig. 7: Reverse filling process under 82 rpm, when the fluid enters the runner (a), fills the runner (b), enters the plate (c), and fills the plate (d)–(f)

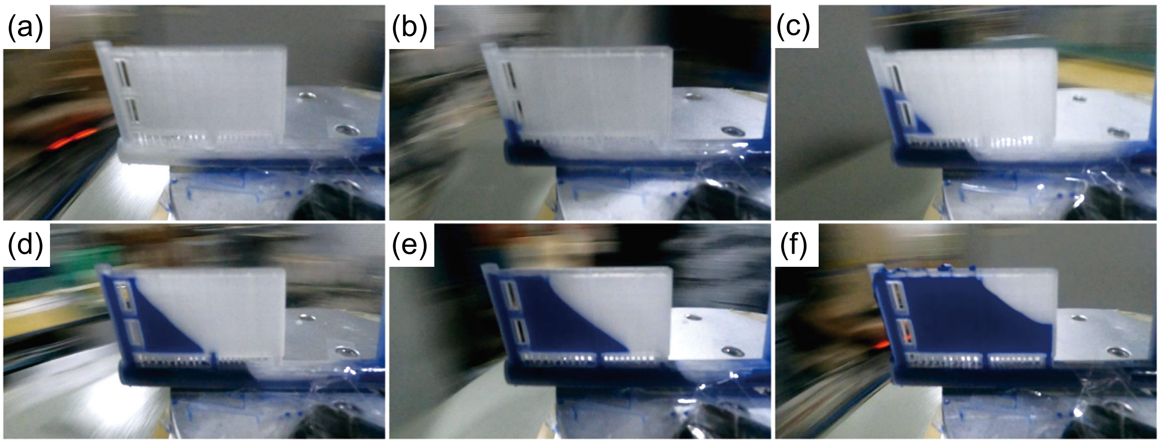

Fig. 8: Reverse filling process under 122 rpm, when the fluid enters the runner (a), fills the runner (b), enters the plate (c), and fills the plate (d)–(f)

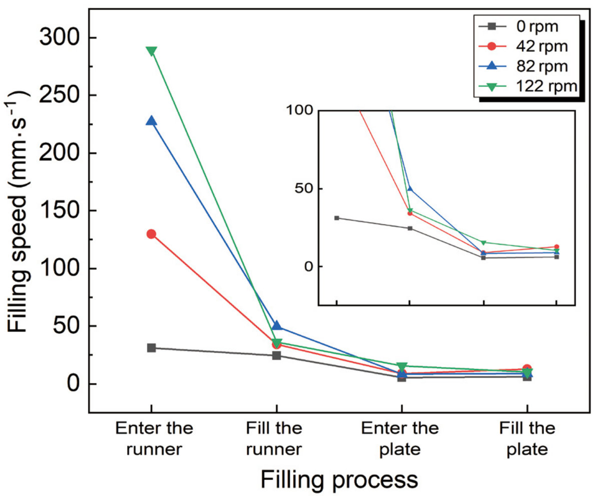

Fig. 9: Filling speed of reverse filling at different rotational speeds

3.3 Filling process of different gating systems

The same method was used to analyze the filling process of the forward filling gating system. Figures 10 and 11 show the filling process of the forward filling gating system at the rotational speed of 0 rpm and 122 rpm. The filling sequence of the forward filling gating system at a higher rotational speed is still horizontal runner, vertical runner, inner runner, and plate. The introduction of centrifugal conditions does not change the filling sequence of the forward filling significantly. However, the liquid quickly moves to the farthest end of the plate under the condition of 122 rpm, and the filling of the plate cavity is also changed to from the outside to the inside, instead of from bottom to top, as shown in Figs. 10(d)–(f) and Figs. 11(c)–(f). This is because the vertical runner of the forward filling gating system is closer to the inside of the cavity, resulting that the centrifugal force in it is not obvious.

Figure 12 shows the comparison of filling speeds of different gating systems at the same rotational speed of 122 rpm. It can be seen from the data that compared with the reverse filling, the forward filling speed has a significant increase in the mid-term, that is, the situation in which the liquid flow is observed to flow rapidly to the farthest end after entering the plate. The difference in filling speed between the two gating systems is relatively small in other processes. Thus, the liquid will complete the filling process faster in the forward filling gating system because of the shorter horizontal runner.

The traditional liquid metal filling mechanism believes that the liquid flow will enter the cavity in a jet shape during forward filling [3]. Therefore, the centrifugal casting must adopt a reverse filling method to ensure the stable filling of liquid metal. According to the experimental results, it is observed that the liquid flows against the inner wall of the cavity continuously during the forward filling process without splashing or interruption of liquid droplets. At the same time, the design of the gating system is more straightforward and the filling time is shorter, which can further improve the production rate of the casting process.

3.4 Filling experiments of casing type mould

Additive manufacturing has significant advantages in preparing test pieces with complex structures. Therefore, a casing type mould was designed and manufactured based on

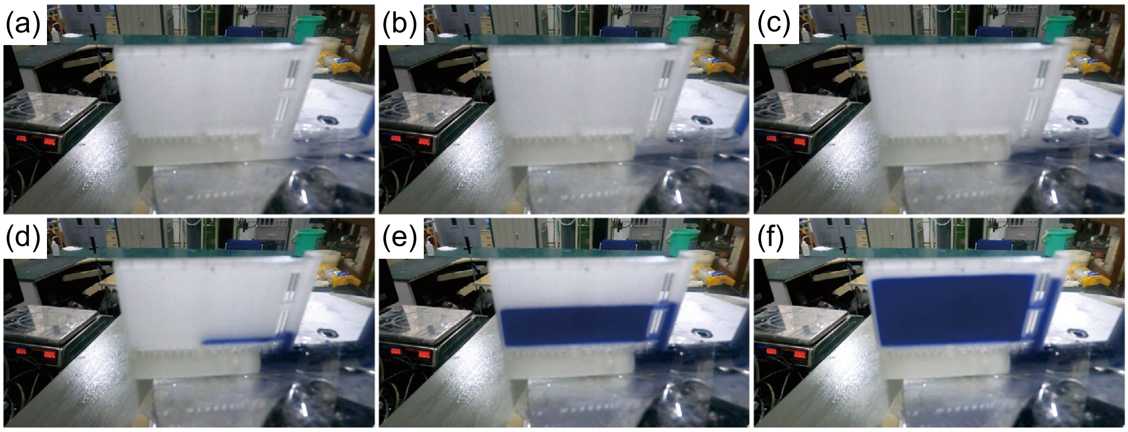

Fig. 10: Forward filling process under 0 rpm, when the fluid enters the runner (a), fills the runner (b)–(c), enters the plate (d), and fills the plate (e)–(f)

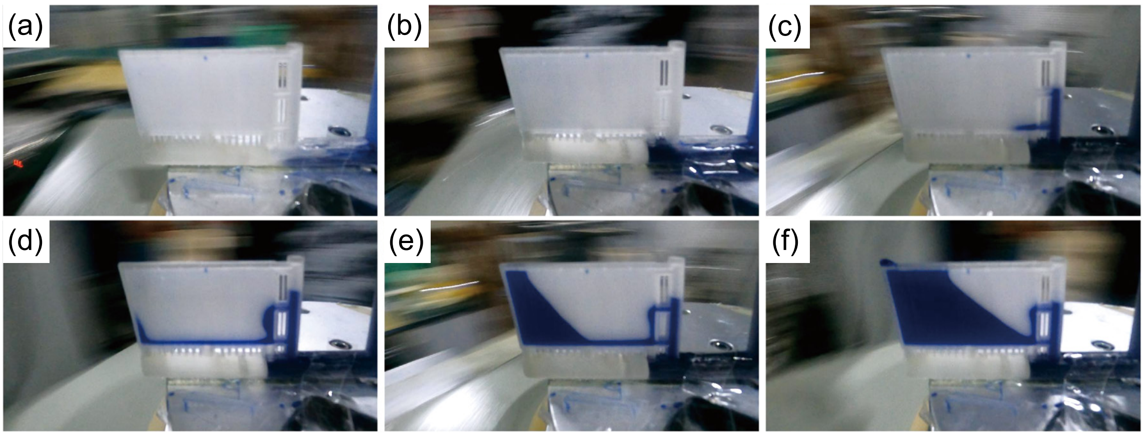

Fig. 11: Forward filling process under 122 rpm, when the fluid enters the runner (a), fills the runner (b), enters the plate (c), and fills the plate (d)–(f)

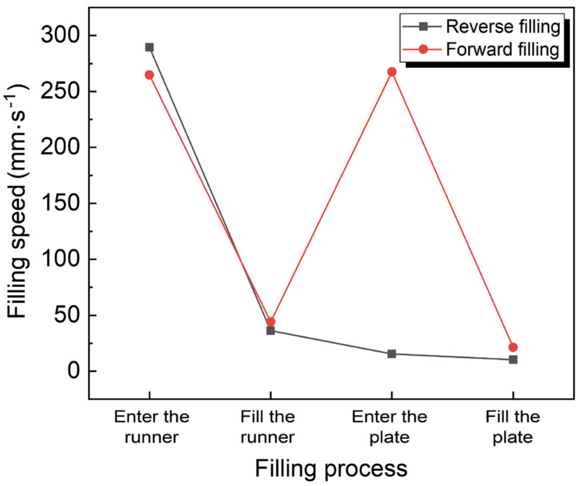

Fig. 12: Comparison of forward and reverse filling speed under 122 rpm

the actual filling and gating system, as shown in Fig. 13. Due to the limitation of the forming size of the printing equipment, the test mould is divided into six small parts to print and splice. The diameter of the outer circle is 260 mm, and the diameter of the inner circle is 130 mm. There are six support bars between the inner and outer circles for connection; the tilt angle of the support bars is 30°. The wall thickness of the test mould is 2 mm everywhere.

Figure 14 is a cross-section view of the position indicated by the red dotted line in Fig. 13, which showing the gating system of the casing type mould. There are annular runners at the bottom of the inner and outer rings, and there are six inner runners to connect the annular runner and the ring. Two runners connect the inner and outer annular runner, inner annular runner and sprue. The red arrows in Fig. 14 indicate the flow direction of the liquid in the gating system. After the liquid enters from

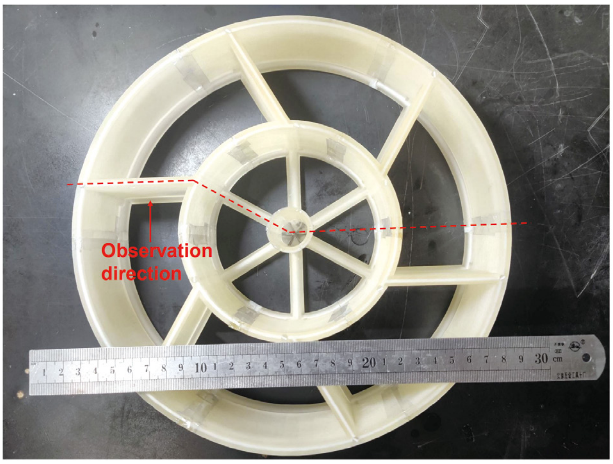

Fig. 13: Casing type test piece prepared by DLP

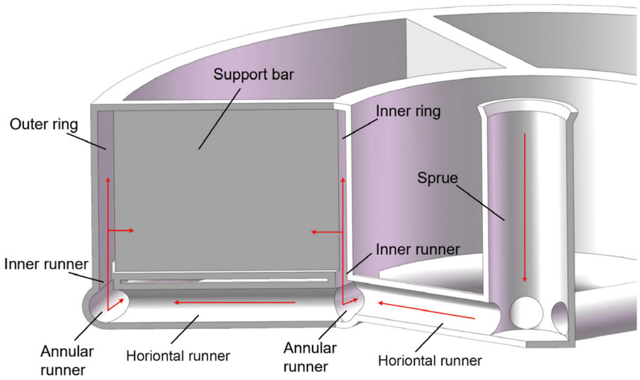

Fig. 14: Gating system of casing type mould

the sprue, it flows into the annular runner through the horizontal runner, and then flows into the part from the inner runners above the annular runner. This filling experiment mainly observes the filling process at the support bars.

Filling experiments were carried out at four different rotational speeds of 0 rpm, 42 rpm, 82 rpm, and 122 rpm. The video capture device was placed between the inner and outer rings to capture the filling process of the support bars and the runner at the bottom. The filling process in the mid-term of the support bar at different rotational speeds are shown in Fig. 15. At lower rotational speeds, the fluid fills the mould from bottom to top, which means that the inner ring, outer ring and support bar will be filled simultaneously. But, at high rotational speeds, although the inner side of the support bar is connected with the inner ring, the fluid will flow to the outside through the bottom runner, that is, the casing type mould is filled in the order of the outer ring to the support bar and then to the inner ring. In conclusion, the filling law of the support bar at different rotation speeds is consistent with that of the reverse filling process in Section 3.1.

4 Conclusions

Transparent moulds with complex structures were successfully prepared using transparent resin by additive manufacturing. The prepared moulds with different filling and gating systems were used in the hydraulic simulation to research the filling

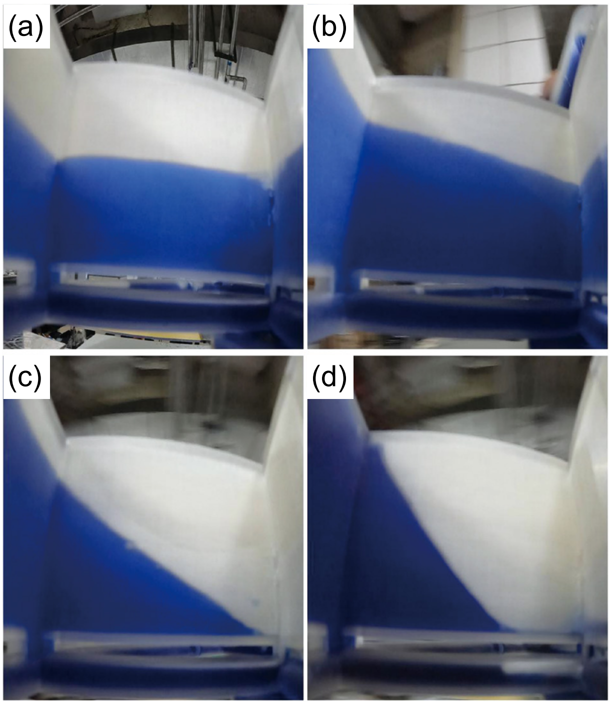

Fig. 15: Filling process of support bar at 0 rpm (a), 42 rpm (b), 82 rpm (c), and 122 rpm (d)

process at different centrifugal rotational speeds, and the following conclusions are obtained:

(1) In the reverse filling process, increasing the centrifugal rotational speed will change the filling sequence of the cavity and gating system. As the rotational speed increases, the inner runners on the outside play the primary role of the filling process instead of the inner runners at the bottom. The angle between the liquid level in the mould and the horizontal plane will increase with the increasing rotational speed. The increase of the rotational speed has a significant influence on the initial filling speed of the runner but has a slight influence on the filling speed of other positions. The filling speed of the fluid in the reverse filling system will gradually decrease from a larger value to a stable value.

(2) The filling sequence of the forward filling system does not change with the centrifugal rotational speed. The filling speed in the mid-term of the forward filling system, that is when liquid flows into the mould cavity from inner runners, is much higher than that of the reverse filling system at the same rotational speed, but the difference in filling speed at other positions is slight. The liquid flow is continuous and stable during the forward filling process, without splashing or interruption of liquid droplets.

(3) The introduction of additive manufacturing technology and transparent photosensitive resin materials into hydraulic simulation can flexibly and quickly manufacture large-sized test moulds with transparent walls and complex structures. The internal filling process of the test mould is easy to observe. The use of imaging equipment that can follow the rotation of the centrifugal platform to shoot can realize the visual observation and analysis of the filling process at different positions of the mould.

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