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Similar physical simulation of microflow in micro-channel by centrifugal casting process

Ming-xing REN[1], Guo-tian WANG[2], Bang-sheng LI[1,2], Zhen-long WANG[3], Heng-zhi FU[2]

1. Key Laboratory of Microsystems and Microstructures Manufacturing of Ministry of Education, Harbin Institute of Technology, Harbin 150001, China;
2. School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China;
3. School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China

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Abstract: By means of similar physical simulation, liquid metal filling flow pattern in the microscale during the centrifugal casting process was studied. It was found that, in microscale, the flow channel with the maximum cross-sectional area was filled first, and the micro flow channels with 0.1 mm in diameter were filled when the rotational speed was increased to 964 r/min. The total fluid energy remained constant during the mould filling, and the changes of cross-sectional area only occurred in the microflow channels with 0.3 mm in diameter. Filling velocity increased with processing time, and a peak value was achieved rapidly, followed by a gentle increase as the process proceeded further. The time required to achieve the peak filling rate decreased dramatically with increase of rotational speed.

Key words: similar simulation; microflow; centrifugal casting; micro-channel

1 Introduction

In recent years, the research on micro forming technology has attracted much attention in the field of advanced manufacturing. Micro precision casting technology, as one of the most promising manufacturing technologies for making micro-components, was developed in 2002. Many research programs on this technology have been conducted worldwide [1−5]. With the aid of centrifugal pouring process, BAUMEISTER et al [1,2] cast micro gears successfully. LI et al [5] and YANG et al [6] have used metal mould and gypsum mould to cast micro-gears with an outer diameter of 580 μm, and micro-rods with a minimum diameter of 100 μm, length to diameter ratio of 200. Micro casting technology is to cast micro-components with the dimension ranging from micrometer to millimeter, thus the scale effects (such as surface energy effect and size effect), which may not be observed in the traditional macro scale casting, tend to be highlighted in the micro-casting process. This could lead to differences in liquid metal flow behavior between the macro scale casting and micro scale casting. At ambient temperature, the liquid flow (water, oil, gas) behavior within the micro pipeline has indicated that the micro fluid flow phenomenon has its unique mechanism and laws, which can be significantly different from the liquid flow behavior of conventional casting processes [7−9]. Liquid metal flow behavior plays an important role in the micro casting processes, in terms of process design and product quality. Therefore, in order to be able to make microcasting components with high accuracy and quality, the microscale liquid metal flow behavior must be thoroughly understood [10]. Due to the invisibility of metal liquid flow during the casting process, it is unlikely to directly observe the liquid metal flow within the mould cavity. At present, numerical simulations are normally used for the analysis of liquid metal flow behavior during conventional macro-scale casting process. However, numerical simulations are only suitable for qualitative analysis, and visual observations cannot be obtained. Therefore, the physical simulation method based on the similarity theory is also developed and employed to realize visualization and quantitative analysis [11−15].

Due to the novelty of microcasting technology, the

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Corresponding author: Ming-xing REN; Tel: +86-451-86403268; E-mail: hitrmx@163.com
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understanding of liquid metal flow behavior during the micro scale centrifugal casting has not been established and the module for microscale simulation has not been developed. Therefore, the reliability of numerical simulation results still needs to be verified. In the present research, based on the similarity theory of physical simulation, a similarity criterion was established between the prototype and the model, and physical simulations were conducted using self-developed device to study the liquid metal flow behavior in microscale under centrifugal casting condition. The results obtained could be used as guidelines for the casting process optimization.

2 Experimental

Figure 1 shows the schematic diagram of device for physical simulation. The machine was a desktop centrifuge (LD4-2A), with a speed of centrifugal rotation up to 4000 r/min. Pouring system was made from transparent PMMA, the pouring channel and mould cavity were made in layered structure. Figure 2 shows the configuration and dimensions of the casting product and pouring channel. An A504kc high speed camera (made in Germany) with maximum sampling rate of up to 500 f/s was employed. The computer connected to the high speed camera had a large capacity (4G) data acquisition card so that the pictures could be recorded continuously whilst casting process.

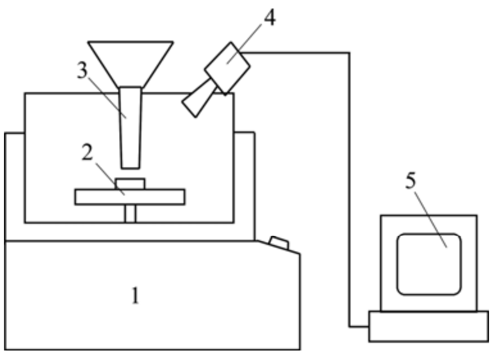

Fig. 1 Schematic diagram of device for physical simulation of hydraulics: 1—Centrifugal system; 2—Pouring system; 3—Funnel; 4—High-speed camera; 5—Computer

In the experiment, Zn−4% Al alloy was the object of physical simulations, and a special water-based tackifier was used to simulate liquid metal. It was found from the theoretical analysis that, the similarity between the liquid metal and physical simulation liquid could be achieved when the actual rotational speed of Zn−4% Al alloy was 1.54 times that of the simulation fluid. The transparent casting mould was fixed on a centrifuge with the high speed camera aligned with pouring system. When the rotational speed was stabilized, simulation fluid was poured into the pouring system. According to the test matrix shown in Table 1, liquid filling and flow behavior in the flowing channels of different diameters were studied at different rotational speeds.

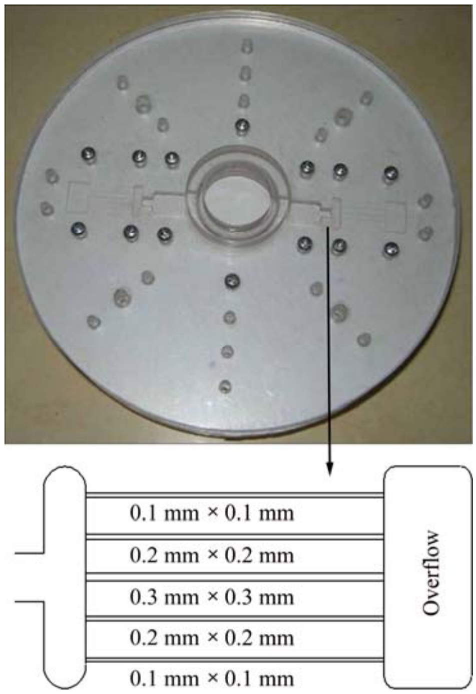

Fig. 2 Optical image of gating system

Table 1 Experimental scheme

Scheme	Rotational speed/(r·min^{-1})	
	Model	Prototype
1	324	500
2	649	1000
3	974	1500

3 Results and discussion

Figures 3−5 show the state of liquid filling at different rotational speeds of 324 r/min, 649 r/min and 974 r/min, respectively. It is found that with the increase of speed, filling time becomes shorter. At the rotational speed of 324 r/min, simulation liquid dose not fill the channels after 3.918 s, as shown in Fig. 3(i). Due to insufficient pressure, the channel is not completely filled at the final stage. When the rotational speed is increased to 974 r/min, it takes only 0.31 s to fill the channels completely, as shown in Fig. 5(i).

3.1 Dynamics process of filling mold of simulation fluid

The flow behavior of simulation liquid is only affected by the gravity effect when the vertical pouring channel is filled, and when the liquid touches the bottom,

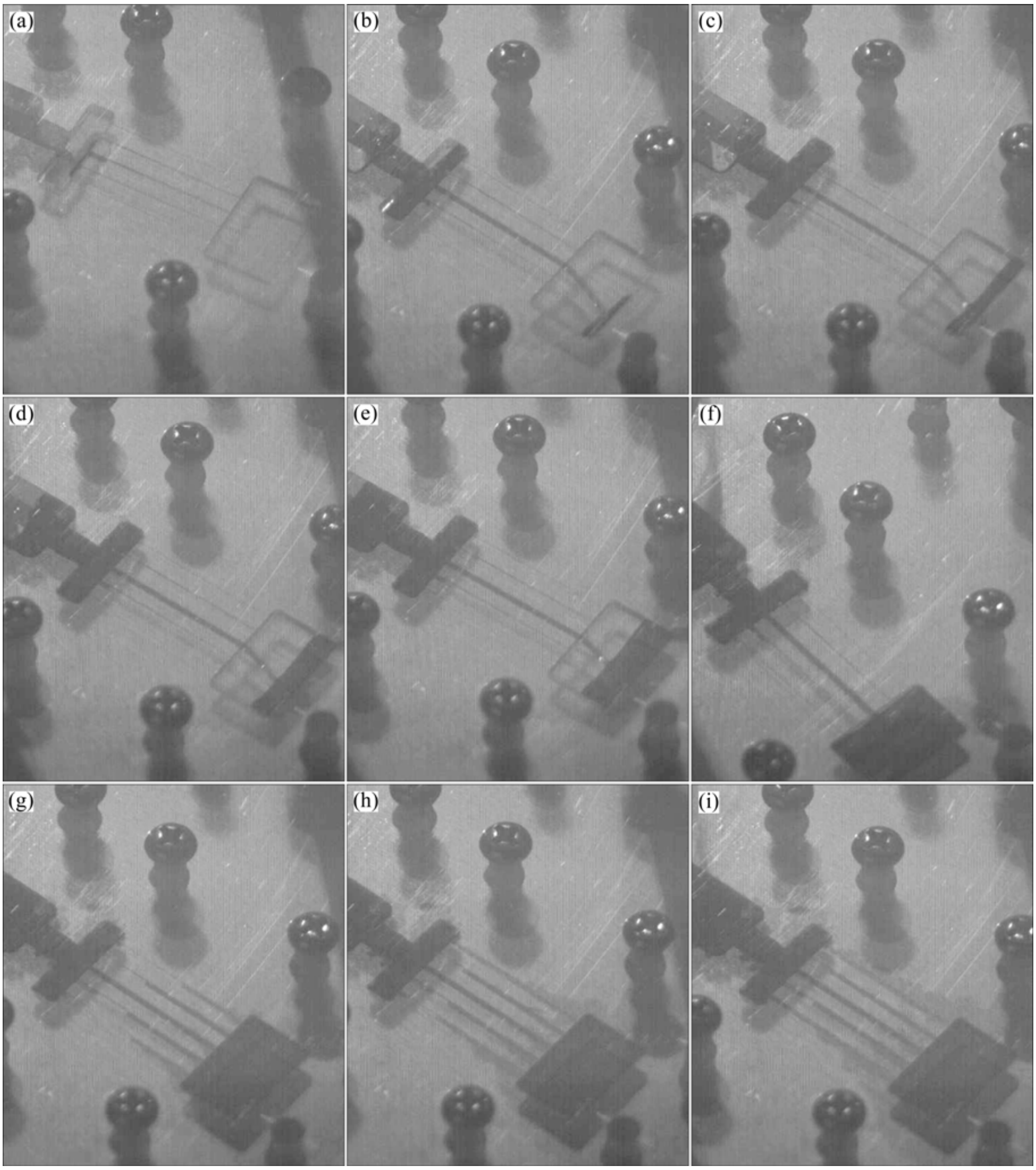

Fig. 3 Filling process of gating system with counter-clockwise rotation in 324 r/min at different time: (a) 0.342 s; (b) 0.916 s; (c) 1.108 s; (d) 1.300 s; (e) 1.492 s; (f) 1.684 s; (g) 2.188 s; (h) 3.148 s; (i) 3.918 s

it starts to be affected by both centrifugal force and Chorios force, meanwhile, the speed of liquid changes from vertical direction into horizontal direction. After the simulation liquid flows into the horizontal channels, the liquid starts to accelerate under the effect of centrifugal force, which increases liquid flow velocity, and the maximum value of centrifugal force is found in the liquid with the maximum axial distance. The channels with greater diameters, i.e. 300 μm, are filled first, as shown in Figs. 3(c), 4(b) and 5(a). As the rotational speed increases, the liquid gradually fills the channels with smaller cross-sectional areas. When the rotational speed is sufficient, liquid can flow into the channels with even smaller diameter (d100 μm), as shown in Fig. 5. When the fluid flows into the overflow tank through the channels, under the effect of centrifugal force, the liquid flows to the furthest point from the rotational axis, in the form of tiny stream, as shown in Figs. 3(d), 4(b) and 5(a). The fluid flow impacts the back wall and the kinetic energy disappears. According to the Bernoulli equation, the total energy of the liquid is constant, i.e. the total value of potential, pressure, translational kinetic and centrifugal rotational kinetic energies is constant. Therefore, in this experiment, after the fluid hits the back

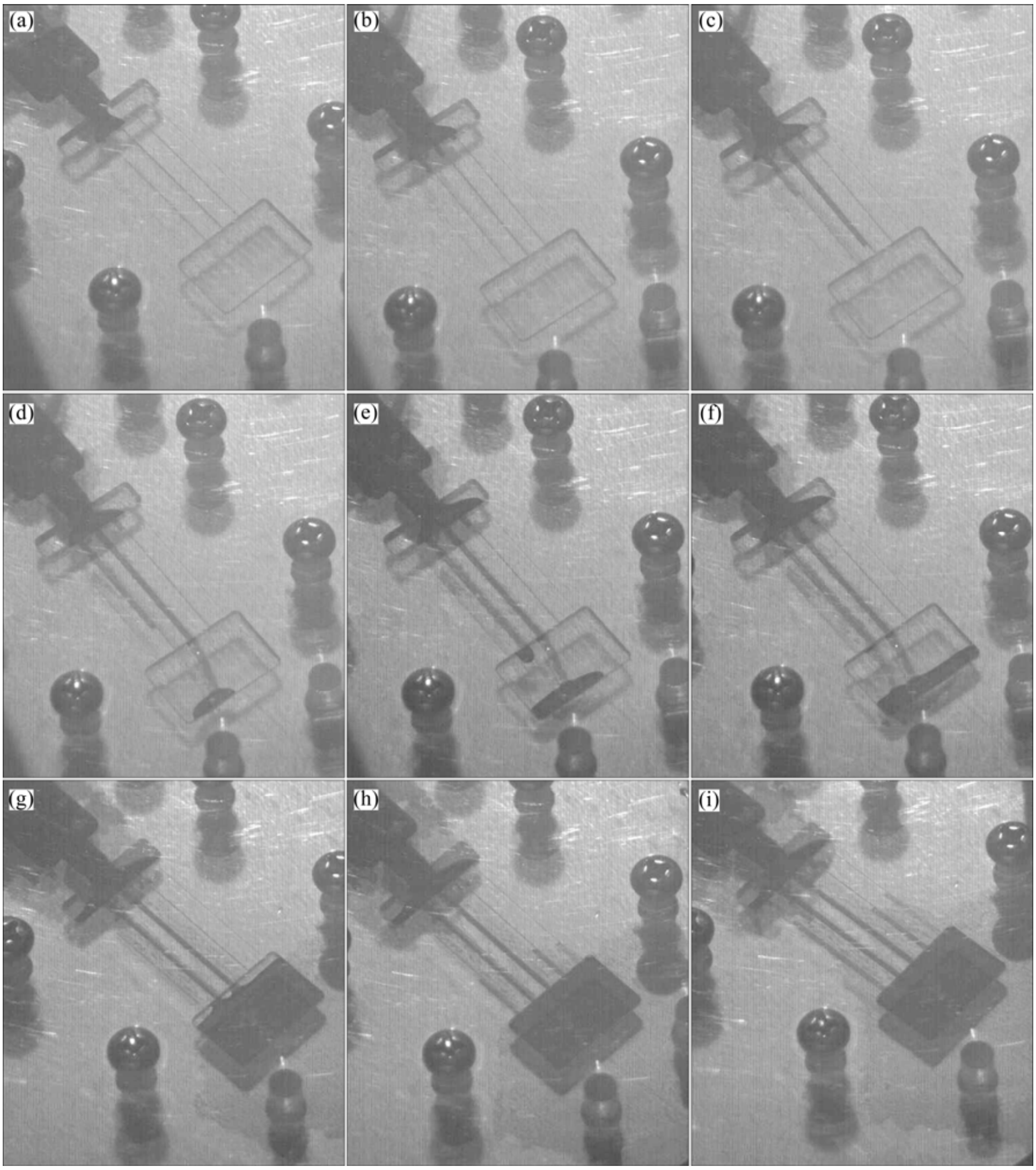

Fig. 4 Filling process of gating system with counter-clockwise rotation in 649 r/min at different time: (a) 0.064 s; (b) 0.142 s; (c) 0.222 s; (d) 0.302 s; (e) 0.382 s; (f) 0.698 s; (g) 0.780 s; (h) 0.860 s; (i) 0.940 s

wall, whilst reversely fills the overflow tank, the potential energy is constant, and centrifugal rotational kinetic energy remains the same, thus all the kinetic energy transforms into pressure energy. The pressure increases dramatically, which increases the driving force for the flow. As the liquid flow proceeds further, pressure energy transforms into kinetic energy, namely the liquid experiences two stages of transformations from kinetic energy to the potential energy and potential energy to kinetic energy. The primary pressure transforms into secondary pressure, and the overflow tank is gradually filled layer by layer, and then the liquid gradually backfills the channels (Figs. 3(i) and 4(i)).

3.2 Influence of rotational speed on cross-sectional area of stream

The comparisons between the experimental results shown in Figs. 3 and 5 indicate that, the cross-sectional area of the simulation liquid in the 300 μm diameter channels decreases with increasing rotational speed. The liquid fills the entire cross section at rotational speed of 324 r/min (Figs. 3(c)−(g)). As the rotational speed increases to 900 r/min, the cross-sectional area of simulation liquid decreases, only wall back filling occurs. This is because that as the rotational speed gradually increases, the effect of Chorios force is more pronounced. Due to the continuity of the liquid, as the filling distance

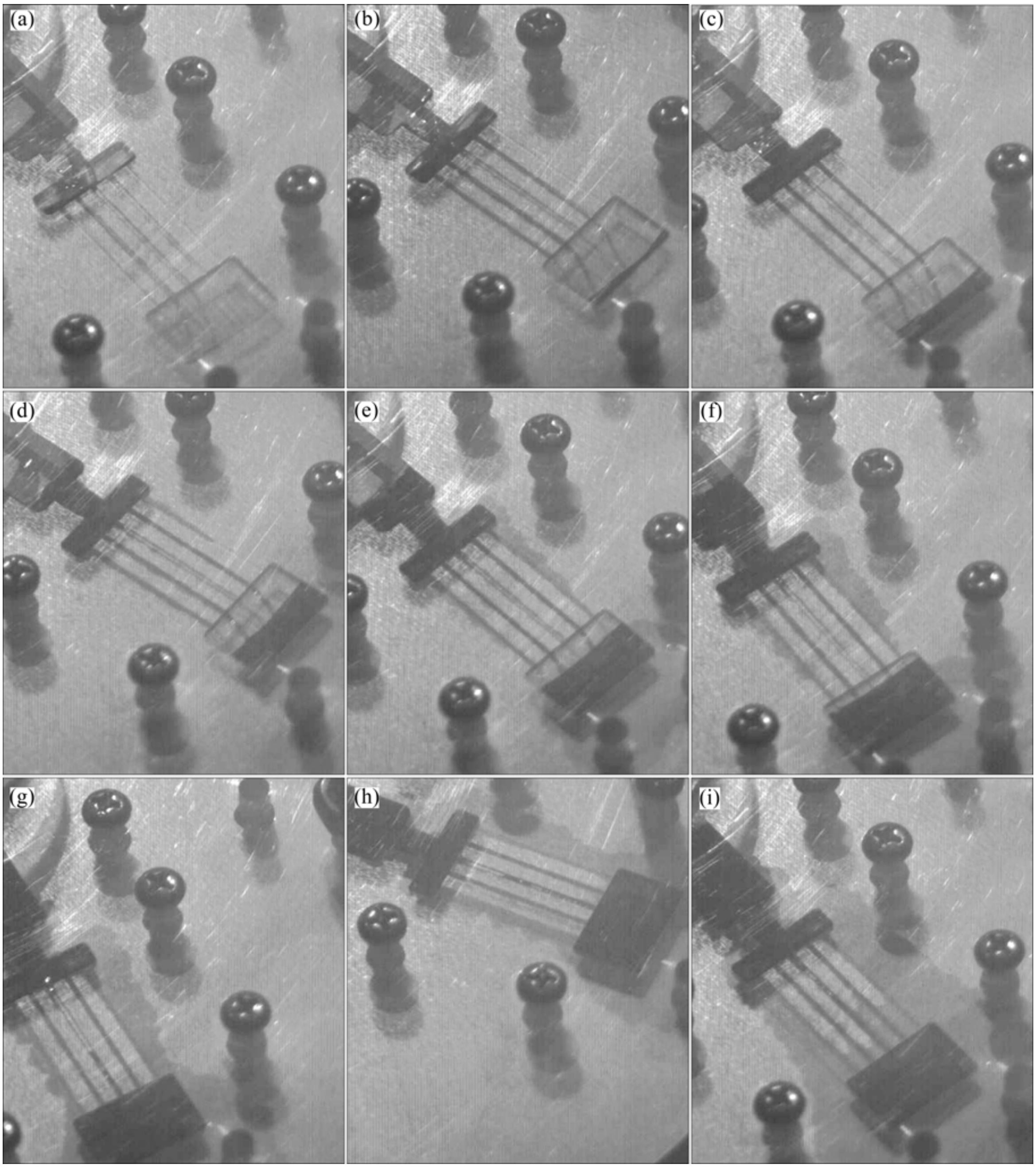

Fig. 5 Filling process of gating system with counter-clockwise rotation in 974 r/min at different time: (a) 0.024 s; (b) 0.066 s; (c) 0.106 s; (d) 0.148 s; (e) 0.188 s; (f) 0.228 s; (g) 0.268 s; (h) 0.272 s; (i) 0.310 s

increases, the velocity of fluid particles increases gradually and the liquid volume close to the walls of horizontal filling channels decreases, i.e. the cross-sectional area of liquid decreases, which is similar to the simulation results of the traditional macro-scale casing [16]. For the micro-casting channels of 0.2 or 0.1 mm in diameter, the variation of cross-sectional area dose not occur, even though the rotational speed is raised to 974 r/min. This can be due to the mass reduction of the liquid, which leads to the force lower than the critical value under the current rotational speed. In addition, the transition of flow behavior from macro to micro scale occurs when the channel diameter is smaller than 300 μm.

3.3 Influence of rotational speed and filling time filling velocity of simulation fluid on

Figures 6−8 show the variation of filling speed as a function of filling time and rotational speed in the channels of different diameters. The flow channels of three different diameters are filled simultaneously only when the rotational speed is 974 r/min, indicating that filling rate increases with the time regardless of channel diameter. At the initial stage of casting, filling rate

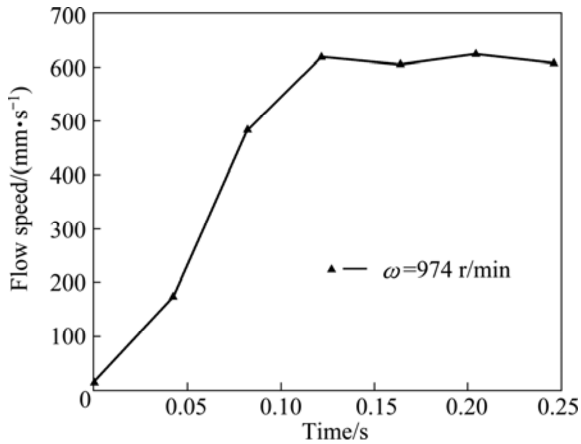

Fig. 6 Relationship between flow speed of liquid and time in channel of *d*0.1 mm

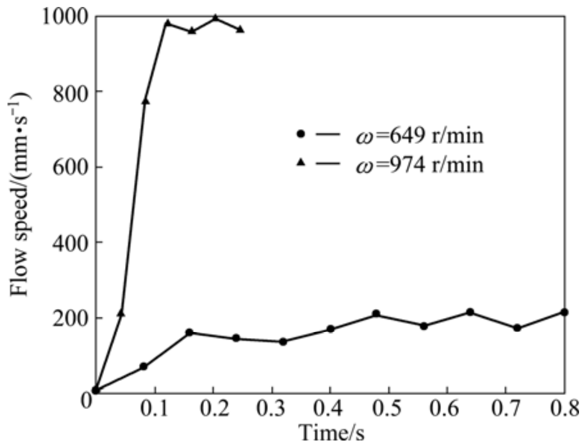

Fig. 7 Relationship between flow speed of liquid and time in channel of *d*0.2 mm

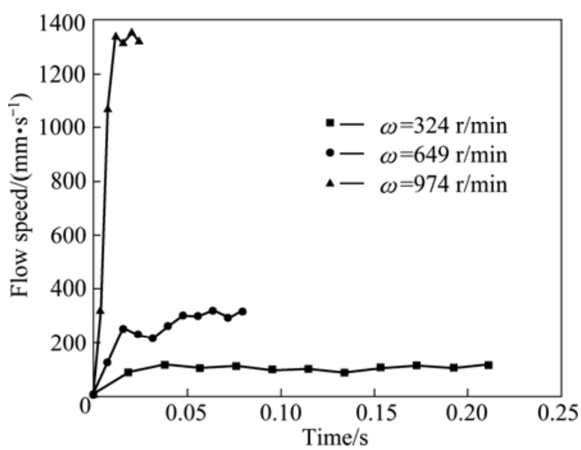

Fig. 8 Relationship between flow speed of liquid and time in channel of *d*0.3 mm

increases significantly and a peak value is achieved rapidly followed by a gradual increase. The trend does not change with rotational speed, but the time required to achieve the peak value of filling rate decreases rapidly, e.g. the time required to achieve peak value is only 0.15 s at the rotational speed of 974 r/min. In addition, the rotational speed has remarkable effects on the filling rate. As shown in Fig. 8, the filling rate increases rapidly with increasing rotational speed, and the peak filling rate at 974 r/min rotational speed is 1.36 m/s. For the flow channels of different diameters, the filling rate increases with increasing channel diameter. This is because the capillary force gradually takes the dominant role with the decrease of cross-sectional area of the channels, which has significantly impeded the liquid flow in the small channels, and thus reduces the filling rate, indicating that the Chorios force is not the major factor to affect the micro-scale mould filling. In the micro-casting process, the resistance of boundary layer also hinders the liquid filling. Under a certain rotation speed, all these factors have led to higher filling rate in the flow channels of bigger diameter. Based on these understandings, the process parameters such as rotation speed and filling time can be determined to ensure that the mould filling is completed before the metal is fully solidified.

4 Conclusions

1) Based on the similarity theory of physical simulation, the relevant parameters can be determined. When the rotation speed ratio between Zn−4% Al alloy and simulation liquid is 1.54, the similarity criterion between the model and prototype can be derived.

2) Under the centrifugal force, the simulation liquid flows preferentially through the horizontal flow channels of the maximum cross-sectional area. During the liquid filling process, the total energy as a summation of potential, pressure, translational kinetic and centrifugal rotational kinetic energies is constant. The fluid has experienced the inter-transformation of kinetic energy and potential energy. The variation of cross-sectional area only occurs in the flow channel of 0.3 mm in diameter. The mould filling rate increases with increasing time and rotation speed. The increase in filling rate is more pronounced at the initial stage, where a peak value is obtained rapidly followed by a gradual increase.

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离心铸造下微尺度充型流动的相似物理模拟

任明星[1]，王国田[2]，李邦盛[1,2]，王振龙[3]，傅恒志[2]

1. 哈尔滨工业大学 微系统与微结构制造教育部重点实验室，哈尔滨 150001；
2. 哈尔滨工业大学 材料科学与工程学院, 哈尔滨 150001；
3. 哈尔滨工业大学 机电工程学院, 哈尔滨 150001

摘 要：利用获得的相似准则，采用相似物理模拟方法，研究离心铸造过程中液态金属在微尺度空间内的充型流动规律。结果表明：在微尺度条件下，模拟流体优先充填横截面积最大的流道，当转速提高到 964 r/min 时，才会同时充填 0.1 mm 的微流道；在充型流动过程中，流体总能量保持不变，流体的自由液面是以转轴为圆心的规则圆弧面；充型速度随时间的增加而增大，迅速达到一个极值，然后随着时间的增加，变化逐渐趋于平缓，同时随着转速的增加充型速度达到峰值的时间也会极剧缩短。

关键词：相似模拟；微流动；离心铸造；微通道

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