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# Effect of holding pressure on the microstructure of vacuum counter-pressure casting aluminum alloy

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ABSTRACT

The effect of holding pressure on the microstructure of vacuum counter-pressure casting aluminum alloy was analyzed by observing the changes of the Si phase size and alloy density. The results show that with the increasing of holding pressure of vacuum counter-pressure casting, the extrusion and infiltration ability among dendrites is enhanced and the microstructure of prepared alloy samples at the same location becomes finer, more uniform and denser. Under the same holding pressure, the smallest extrusion and infiltration ability takes place at the middle of sample. Accordingly, from the pouring gate to middle, the microstructure of vacuum counter-pressure casting aluminum alloy sample becomes coarser, more non-uniform and less dense, while the microstructure from the middle to top becomes finer, more uniform and denser.



## 1. Introduction

Vacuum counter-pressure casting technology is a kind of advanced counter-gravity method and has been employed widely in precision forming field. Adopting the advantages of vacuum filling mould under low pressure and melts crystallizing under high pressure, this fabrication technology has characteristics of vacuum suction casting, low-pressure casting and pressure kettle casting concurrently, which produce predominant filling hydrodynamics and notable solidification mechanism in comparison with the traditional casting process [1,2]. So, it has enormous vitality in producing near net shape, large scale, thin wall and complicated nonferrous alloy castings in many fields, such as aviation, spaceflight, national defense and automobile industry.

Generally speaking, one of keys to obtain high quality products for vacuum counter-pressure casting is the control of crystallization and solidification, which ensures castings to possess good solidification feeding condition, dense microstructure and excellent mechanical property. Moreover, holding pressure is an important parameter for vacuum counter-pressure casting technology, and significantly affects castings quality [3]. At present, vacuum counter-pressure casting technology and equipment have been studied as a focal problem in the foundry industry. The advanced counter-pressure casting equipment and technology have been researched in many countries, such as Bulgaria, Japan, Germany, Italy and some other developed countries [4,5]. In China, some university and institutes have also studied and explored on vacuum counter-pressure casting equipment and technology, such as control system, filling process and numerical simulation [6–8]. Accompanying the development of counter-pressure casting technology, a deep understanding of the relations between the processing conditions and resultant microstructure characteristic has important theoretical significance for fabrication of high quality and thin wall precision castings. Akad [4] studied crystallization process of counter-pressure casting, and discussed infiltration process through the growing crystal lattice during alloy solidification, so counter-pressure casting process had good feeding condition and could obtain dense castings. Meanwhile, Kovacheva et al. [9] investigated influence of the counter-pressure casting conditions on the microstructural characteristics of AlSi7Mg castings, and concluded aluminum alloy dendrites could take place microplastic deformation phenomenon under counter-pressure casting accompanied by infiltration through the growing dendrite, and obtained microstructure was fine and of no porosity. Moreover, Katzarov et al. [10] studied porosity formation in axisymmetric castings produced by counter-pressure casting method, and concluded an important parameter that influences the porosity formation in a counter-pressure casting process is the solidification pressure, which showed bigger solidification pressure could obtain dense microstructure. These pioneering work offer essential theory basis for the future research of counter-pressure casting technique.

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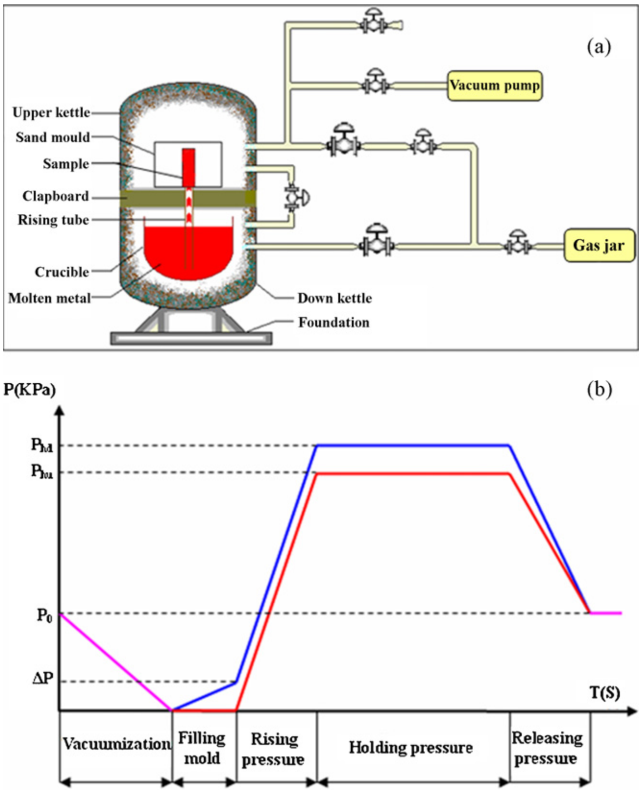


**Fig. 1.** Equipment and technical graph of vacuum counter-pressure casting (a) equipment, (b) technical graph.

To give a further investigation of the effects of holding pressure on the microstructure of vacuum counter-pressure casting , the present paper focuses on the microstructure evolution of aluminum alloy A356, i.e., Si phase size and alloy density, under different holding pressure and different location. Appling the pressure dependent extrusion and infiltration ability, the observed experimental results can be well explained.

## 2. Experimental procedure

The vacuum counter-pressure casting equipment used in the present work is shown in Fig. 1(a), and it includes upper and down pressure kettle, Meanwhile, the mould was settled in the upper pressure kettle and the holding furnace was kept inside the down pressure kettle. The whole vacuum counter-pressure casting process can be divided into five stages, i.e., vacuumization, filling mould, rising pressure, holding pressure and releasing pressure, as shown in Fig. 1(b). It should be noted that the effect of holding pressure on the microstructure of vacuum counter-pressure casting aluminum alloy occurs in holding pressure stage.

The simplest cylinder samples with a diameter of 30 mm and a length of 250 mm, sand mould and aluminum alloy A356 were adopted in this experiment. The alloy ingot was melt in a graphite crucible kept in an electric resistance furnace. When the temperature of furnace was raised to 700 °C and held for 20 min, subsequently, through a feeding tube the molten metal was pressed into a sand mould cavity with a preheated temperature of 200 °C under a designed filling pressure difference of 40 kPa. The sand mould cavity was controlled at a negative pressure of 15 kPa. So, the cavity filling time is about 0.3 s. Four different holding pressure parameters (75, 200, 320 and 450 kPa) were used with other same technical parameters of vacuum counter-pressure casting, as shown in Table 1. By using different vacuum counter-pressure casting aluminum alloy samples, four test bars were obtained in the experiment, which were further cut into seven segments from pouring gate to top and numbered from No.1–1 to No. 1–7, No. 2–1 to No. 2–7, No. 3–1 to No. 3–7 and No. 4–1 to No. 4–7, respectively.

In order to compare and analyze the microstructure of samples at the same location under different holding pressure, the samples such as No. 1–1, No. 2–1, No. 3–1 and No. 4–1 were selected to be observed. In the same way, in order to compare and analyze microstructure of the samples at different location under same holding pressure, the samples such as No. 4–1, No. 4–2, No. 4–3, No. 4–4, No. 4–5, No. 4–6 and No. 4–7 were selected. These samples were prepared by grinding paper from 320 to 1200 grit and metallographically polished with 1 μm alumina, and subsequently ultrasonically cleaned and etched using a reagent comprising 5 ml HF and 95 ml distilled water. The microstructures were examined using Germany Lycra PEA-124 type image analyzer. Meanwhile, the density of the samples was measured by Archimedes' method.

## 3. Results and discussion

### 3.1. Microstructure of the samples at the same location under different holding pressure

Under different holding pressure, the microstructures of vacuum counter-pressure casting aluminum alloy samples at the same location such as No. 1–1, No. 2–1, No. 3–1 and No. 4–1 are shown in Fig. 2. As can be seen clearly, with the increase of holding pressure, the morphology of Si phase at the same location changes from coarse to fine and its distribution becomes more uniform. From Fig. 3, it can be seen that the size of Si phase decreases gradually from 72 to 26 μm. Accordingly, the number of Si phase increases significantly.

Through testing the density of vacuum counter-pressure casting aluminum alloy samples at the same location, the relationship of the density with holding pressure of the above mentioned samples is shown in Fig. 4. Obviously, the density of vacuum counter-pressure casting aluminum alloy samples at same location is improved with the increase of holding pressure and this enhancing trend is strengthened when pressure changes from the negative to positive pressure. When holding pressure is low, the microstructure of the samples at some locations such as No. 1–1 even appears porosity phenomenon, as indicated in Fig. 5(a), which corresponds to the location at pouring gate under a negative pressure of 75 kPa. Therefore, with the increase of holding pressure, the microstructure of vacuum counter-pressure casting aluminum alloy samples at the same location is more and more dense.

In previous studies [11], it was showed that the feeding process of alloy solidification is realized through flow of molten metal. For bigger driving force, the promotion of the liquid flow is enhanced, which generates the stronger feeding ability of the molten metal, as well as the denser microstructure. As mentioned above, vacuum counter-pressure casting technology adopts crystallizing under high pressure. So, the higher pressure is applied on molten metal during solidification process, and the feeding driving force of molten metal among dendrite space is very big. Moreover, as the bigger external pressure was applied, the bigger feeding driving force can be obtained. Therefore, the molten metal can pass through the narrow space among solidified dendrite to feed shrinkage area successfully.

During vacuum counter-pressure casting, the behavior of feeding driving force which promotes the molten metal flow toward solidification shrinkage area through narrow dendrite space is named as extrusion and infiltration ability. Meanwhile, the cor-

**Table 1**
Technical parameter of vacuum counter-pressure casting in the experiment.

| Sample No. | Vacuum degree (KPa) | Pressure difference (KPa) | Time of holding pressure (s) | Holding pressure (KPa) |
|---|---|---|---|---|
| 1 | 15 | 40 | 400 | 75 |
| 2 | 15 | 40 | 400 | 200 |
| 3 | 15 | 40 | 400 | 320 |
| 4 | 15 | 40 | 400 | 450 |

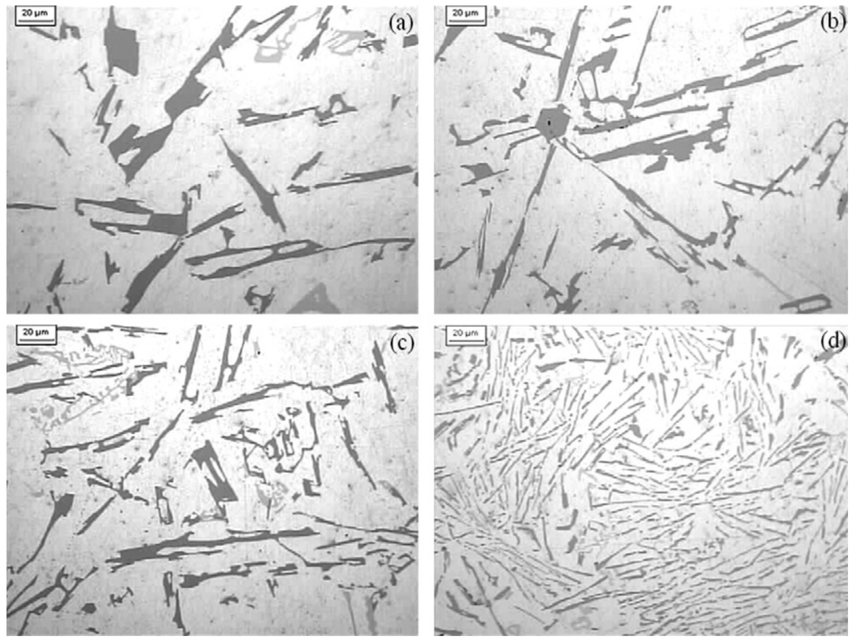


**Fig. 2.** Microstructure of the samples at same location under different holding pressure (a) No. 1–1, (b) No. 2–1, (c) No. 3–1, (d) No. 4–1.

responding feeding driving force can be evaluated by the flux of molten metal passed through narrow dendrite space to feed solidification shrinkage. Because dendrite space in solidified area is very small and is normally 10–100 μm, the flow channel of molten metal is actually very narrow, and flow behavior may be regard as laminar flow pattern.

Under the laminar flow pattern conditions, the extrusion and infiltration ability of molten metal may be calculated by Eq. (1), as listed below [4]:

$$\Delta G = \frac{KP_e}{\mu L} F \cdot \Delta\tau \tag{1}$$

where $\Delta G$ is metal capacity of extrusion and infiltration in shrinkage cavity, $\mu$ is dynamical viscosity coefficient of molten metal, $L$ is depth of extrusion and infiltration, $P_e$ is pressure arousing extrusion and infiltration, $F$ is area of extrusion and infiltration, $\Delta\tau$ is time of extrusion and infiltration, and $K$ is infiltration coefficient.

After castings shape, pouring process and alloy compositions can be determined and $\Delta G$ is in direct proportion to $P_e$. Normally, the pressure $P_e$ for extrusion and infiltration ability can be solved by the following equation [12]:

$$P_e = P_h + P_c - P_s - P_g \tag{2}$$

where $P_h$ is holding pressure, $P_s$ is static pressure of molten metal exerting on extrusion and infiltration surface, $P_g$ is pressure separating out gas between dendrite in extrusion and infiltration layer, and $P_c$ is capillary force.

When $P_c$, $P_s$, $P_g$ and other factors are same under vacuum counter-pressure casting, the extrusion and infiltration ability at same location is determined mainly by holding pressure $P_h$, as can be inferred from the Eqs. (1) and (2). Therefore, the stronger extrusion and infiltration ability will improve the flow ability of aluminum alloy through narrow channel among solidified dendrite, which is advantageous for the increase of microstructure dense. Furthermore, even if aluminum alloy dendrites form contin-

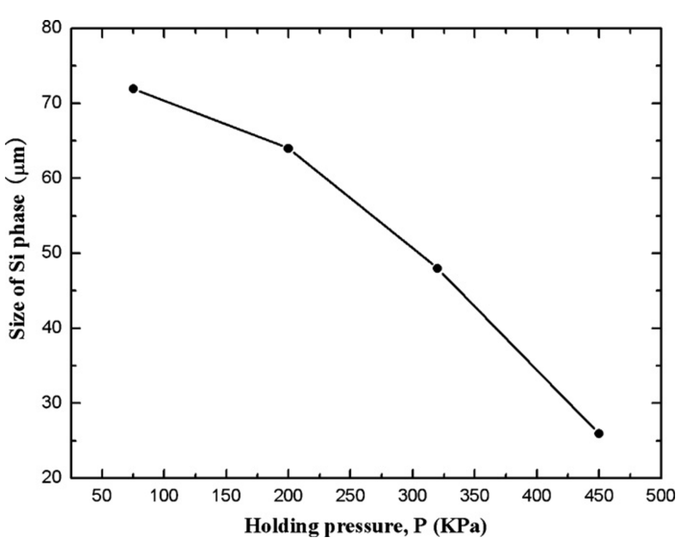


**Fig. 3.** Size of Si phase of the samples at same location under different holding pressure.

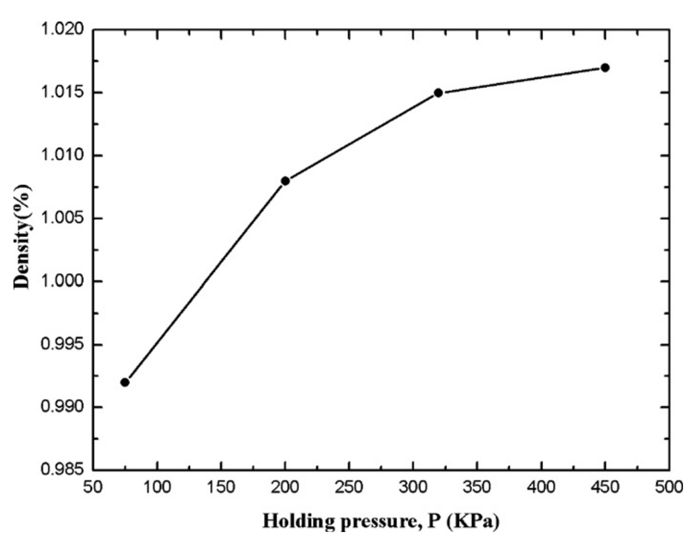


**Fig. 4.** Density of the samples at same location under different holding pressure.

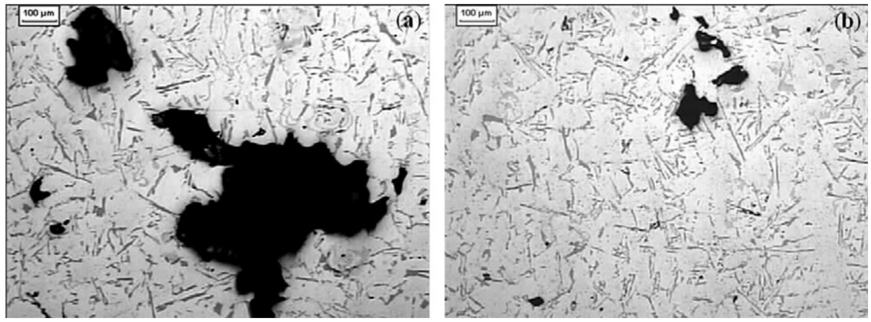


**Fig. 5.** Porosity microstructure of the samples (a) No. 1–1, (b) No. 2–1.

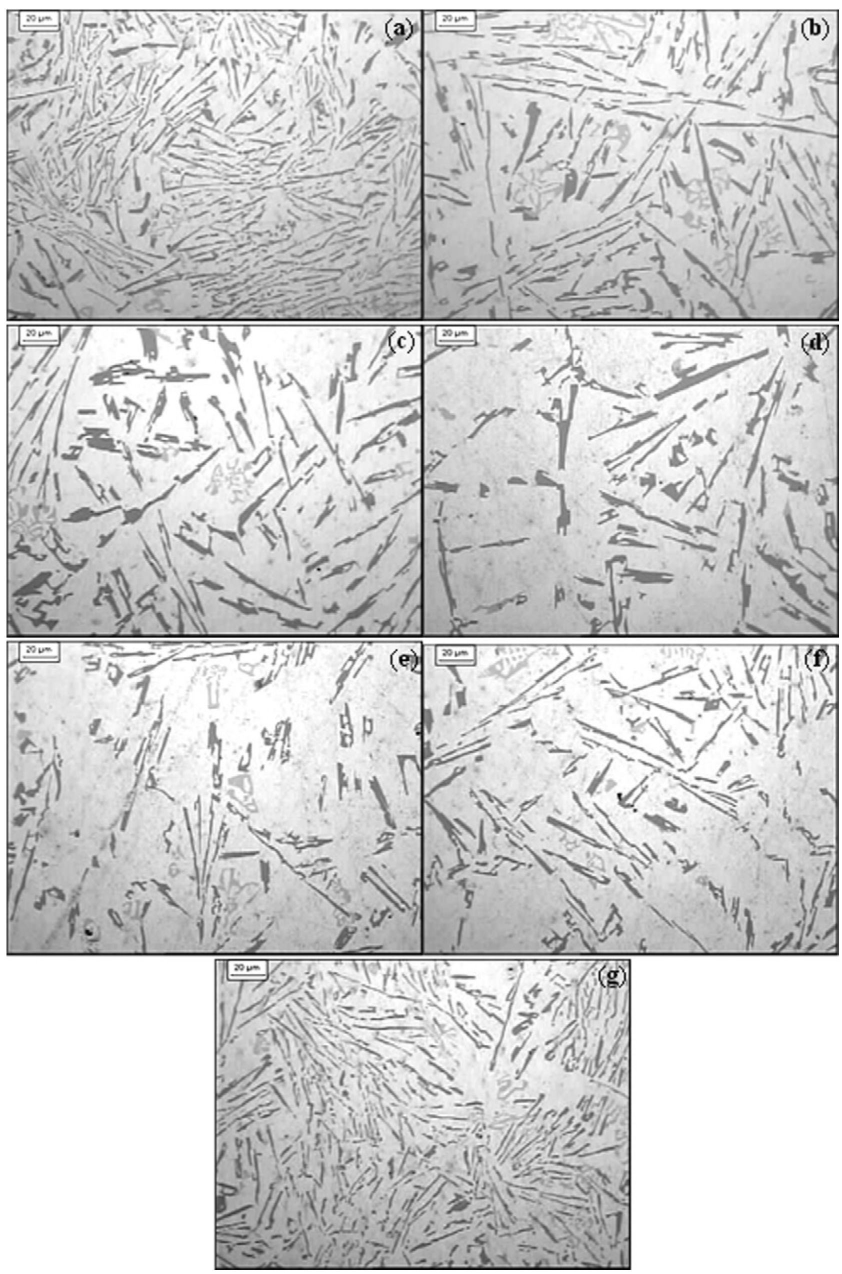


**Fig. 6.** Microstructure of the samples at different location under same holding pressure (a) No. 4–1, (b) No. 4–2, (c) No. 4–3, (d) No. 4–4, (e) No. 4–5, (f) No. 4–6, (g) No. 4–7.

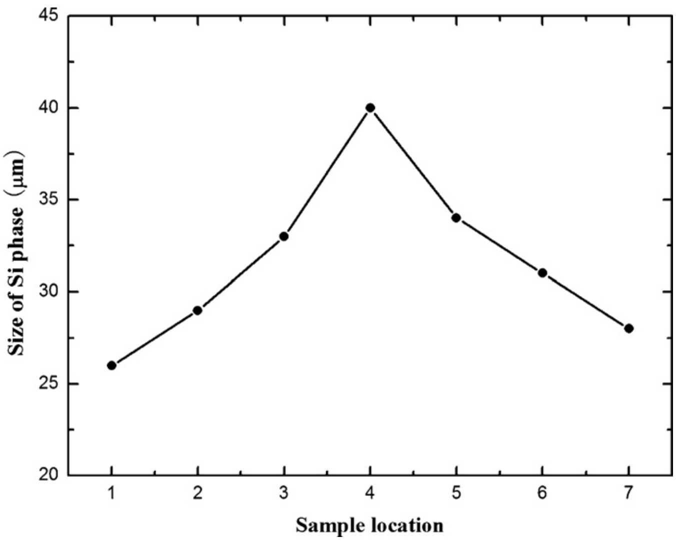


**Fig. 7.** Size of Si phase of the samples at different location under same holding pressure (Note that sample location from 1 to 7 corresponds to sample from 4–1 to 4–7).

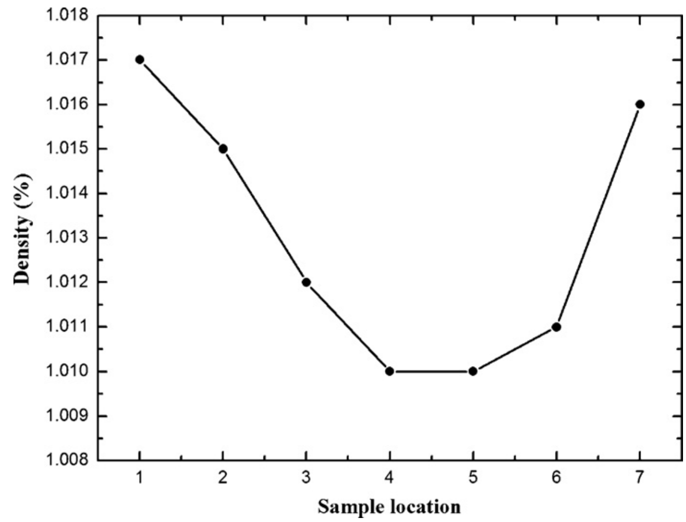


**Fig. 8.** Density of the samples at different location under same holding pressure (Note that sample location from 1 to 7 corresponds to sample from 4–1 to 4–7).

uous skeleton during extrusion and infiltration process, they will be rushed and broken by the molten metal flow when their strength is lower than the extrusion and infiltration pressure $P_e$, resulting the increase of dissociated grain, the refinement of grain and the opening of flow channel. Accordingly, with the increasing of holing pressure for counter-pressure casting aluminum alloy, liquid can flow for a long time and filter dendrite gap, which promotes finer Si phase, more uniform distribution and denser microstructure.

### *3.2. Microstructure of different location under same holding pressure*

Under same holding pressure, the microstructures of vacuum counter-pressure casting aluminum alloy samples at different location such as No. 4–1, No. 4–2, No. 4–3, No. 4–4, No. 4–5, No. 4–6 and No. 4–7 are shown in Fig. 6. Obviously, under the same holding pressure of 450 kPa, the Si phase morphology of aluminum alloy samples from the pouring gate to the middle location becomes coarser and the grain number decreases significantly. Moreover, their distribution appears more non-uniform. Accordingly, the size of Si phase increases from 26 to 40 μm, as shown in Fig. 7. However, the size of Si phase from the middle to top location turns fine gradually from 40 to 28 μm, and their distribution is more uniform, accompanying the increase of the grain number.

Through testing the density of vacuum counter-pressure casting aluminum alloy samples at different location such as No. 4–1, No. 4–2, No. 4–3, No. 4–4, No. 4–5, No. 4–6 and No. 4–7, the curve of the density change at different location is shown in Fig. 8. Seen from Fig. 8, under same keeping pressure of 450 kPa, the density of vacuum counter-pressure casting aluminum alloy samples at pouring gate location is the largest. Form pouring gate to the middle location, the density decreases gradually firstly and reaches its minimum at the middle location. It should be noted that a small amount of porosity phenomenon can be found at the middle location of sample under lower holding pressure of 200 kPa, as shown in Fig. 5(b). Subsequently, it increases gradually from the middle to top location. Therefore, under the same holding pressure, the microstructure of vacuum counter-pressure casting aluminum alloy samples from the pouring gate to the middle location gets less dense and the microstructure from the middle to top location is more and more dense.

According to hydrodynamics principles, the pressure loss of molten metal always exists during molten metal flow, and the total pressure loss $\sum P$ can be expressed as [13]:

$$\sum P = P_h = P_x = \frac{8\upsilon\mu x}{\delta^2} \quad (3)$$

$$P_x = P_h - \frac{8\upsilon\mu x}{\delta^2} \quad (4)$$

where $P_x$ is Pressure at $x$ location among dendrite and $\upsilon$ is flow velocity of molten metal.

Seen from the vacuum counter-pressure casting technical graph (Fig. 1(b)), relationship of holding pressure at upper kettle and down kettle can be expressed as:

$$P_{hu} = P_{hd} - \Delta P \quad (5)$$

where $P_{hu}$ is holding pressure at upper kettle, $P_{hd}$ is holding pressure at down kettle and $\Delta P$ is pressure different during filling mould.

During crystallization and solidification process of vacuum counter-pressure casting, the holding pressure at pouring gate is always $P_{hd}$. Meanwhile, the holding pressure at top is always $P_{hu}$. Under the same holding pressure, the pressure loss along the flow channel leads to the reducing of corresponding liquid pressure during molten metal flow process, as can be indicated from Eq. (4). As a result, from the pouring gate to middle location, the pressure which promotes liquid to flow decrease gradually, and the extrusion and infiltration ability among dendrite is decreased. Accordingly, the formed Si phase of aluminum alloy samples from the pouring gate to middle location get coarser and their distribution is more non-uniform. Moreover, the number of Si phase decreases significantly and the microstructure get less dense. In the same way, from the top to middle, extrusion and infiltration ability among dendrite is also decreasing, so the microstructure of vacuum counter-pressure casting aluminum alloy samples get coarser, more non-uniform and less dense.

## 4. Conclusions

With the increase of holding pressure, the extrusion and infiltration ability among dendrites gets strong, and the microstructure of vacuum counter-pressure casting aluminum alloy samples at the same location becomes finer, more uniform and denser. Under same holding pressure, the smallest extrusion and infiltration ability takes place at the middle of sample, and the microstructure of vacuum counter-pressure casting aluminum alloy samples from the pouring gate to middle location becomes coarser, more non-uniform and less dense, while the microstructure from the middle to top location becomes thinner, more uniform and denser. In order to obtain dense and uniform microstructure, the high holding pressure must be employed during crystallization of vacuum counter-pressure casting.

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