Effect of centrifugal counter-gravity casting on solidification microstructure and mechanical properties of A357 aluminum alloy

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Abstract: To investigate the influence of Centrifugal Counter-gravity Casting (C3) process on the solidification microstructure and mechanical properties of the casting, A357 aluminum alloy samples were produced by different process conditions under C3. The results show that C3 has better feeding capacity compared with the vacuum suction casting; and that the mechanical vibration and the convection of melts formed at the centrifugal rotation stage suppress the growth of dendrites, subsequently resulting in the refinement of grains and the improvement of mechanical properties, density and hardness. A finer grain and higher strength can be obtained in the A357 alloy by increasing centrifugal radius and rotational speed. However, casting defects will appear near the rotational axis and the mechanical properties will decrease once the rotational speed exceeds 150 r·min⁻¹.

Key words: centrifugal counter-gravity casting; vacuum suction casting; rotational speed; solidification feeding

Small, complex, thin-walled components are very difficult to cast by conventional casting technology; due to complex structure, high machine performance, high dimensional accuracy, thin wall and asymmetric wall thickness. The present special casting method, Vacuum Suction Casting (VSC), possesses good filling ability, controlled filling speed, and high utilization rate of metal, etc. It is considered one of the ideal processes to produce these components [1-3]. However, due to existing deficiencies such as small solidification feeding pressure and casting solidification under negative pressure environment, it is easy to form defects, such as shrinkage cavity and shrinkage porosity, which limit the application of this technology [4-5]. In order to deal with the above disadvantages, the Vacuum Low-Pressure Casting technology and the Vacuum Counter-Pressure Casting technology have been applied. However, the casting equipment of these technologies with its high gas tightness, complicated pneumatic control system, and low production efficiency, is limited in practical production.

The Hitchiner Company in the United States applied for a patent named Centrifugal Counter-gravity Casting (C3) method and device in 2002 [6]. Combined with strong feeding ability of the vertical centrifugal casting and good filling ability of VSC, C3 process has some advantages in manufacturing small complex thin-walled castings, such as strong filling ability, controlled filling speed, strong feeding power, compact solidified structure, and high rate of metal utilization. The C3 method can also be applied to aluminum alloys, copper alloys, stainless steels, metal matrix composites, titanium alloys, nickel base alloys, and so on. In addition, through integration automation control technology and the pattern assembly design, C3 has high production efficiency and casting yield. Currently, C3 has been successfully used in the United States large casting production enterprises [7, 8]. But, for C3 technology, the process parameters have very important influence on the filling process, solidification microstructure and mechanical properties. Its forming mechanism and solidification feeding regularity need further in-depth research. Therefore, this paper describes some related experimental research.
1 Experimental procedure

The schematic diagram of the C3 process is shown in Fig. 1. The investment casting mould was fixed in the rotatable suction chamber and the riser tube was connected with the sprue. At the pouring stage, differential pressure was built as the chamber rotated. Melts flowed into the mould, and then solidified under the common action of gas pressure and centrifugal force. As the vacuum condition was removed and the chamber stopped rotating, melts in the gates flowed back to the crucible. Based on the above operating principle, our team designed and manufactured the C3 equipment that satisfied the production of castings using the C3 method.

This casting process was performed on independent C3 equipment to study the effect of C3 process on the microstructure and mechanical properties of A357 alloy. A three-dimensional model of the casting mould was designed and is shown in Fig. 2. It has a cross-gating system with six bars in the vertical direction and eight bars in the horizontal direction. The upright bars were numbered V1, V2 and V3 from inside to outside, and the horizontal bars were named H1, H2, H3, and H4 from the bottom up. The size of the tensile test bar is shown in Fig. 3. In order to study the differences in microstructure and mechanical properties at different process parameters, the H4 bar was elected, from the areas labeled A, B and C, also as shown in Fig. 2. All the moulds were prepared by investment casting. The casting details were as follows: pouring temperature 710 ℃, mould preheated to 240 ℃, filling pressure at -25 kPa, holding pressure at -40 kPa, filling speed and holding pressure speed both at -3 kPa·s⁻¹, centrifugal rotation after filling for 3 s, holding pressure time for 400 s, and centrifugal rotational speed at 0, 50 and 150 r·min⁻¹.

After being heat treated in T6 condition, tensile tests of C3 samples were performed on the electronic tensile testing machine INSTRON-382. The tensile rate was 1 mm·min⁻¹. An OLYMPUS GX71 optical microscope was used to observe the microstructures. The drainage method was used to measure the density variation. The micro-hardness measurements were taken on a HVS-50 digital micro-hardness tester.

2 Results and discussion

2.1 Effect of process parameters on mould filling

Within the mould, samples were totally filled with the rotational speed at 0 to 150 r·min⁻¹. Figure 4 shows an observed cavity that was found in the casting at 150 r·min⁻¹. Figure 5 shows an inner sinking at H3 and H4 bars near the end face of the sprue gate. During mould filling, a sequence of things happened. The casting mould started to rotate after the filling process has finished, and the melts moved into a circle around the rotational axis. Liquid away from the rotational axis rose, while liquid at the axis fell; finally presenting a parabolic shape of free surface.
With increasing rotational speed, the centrifugal force and static pressure on the inside of mould was larger, and a similarly extended decline was observed on the free surface of liquid at the central axis. As the rotational speed kept rising, the lowest point of the free surface reached the runner of the gate. The melts near the free surface were not fed enough, so cavities appeared.

2.2 Effect of process parameters on solidification structure

The metallographic structures of cross sectional centers at A, B and C of sample H4 are shown in Fig. 6, Fig. 7 and Fig. 8, at rotation speeds of 0, 50 and 150 $\text{r} \cdot \text{min}^{-1}$, respectively. It was observed that when the rotation speed was 0, in the suction casting condition, no obvious difference of grain sizes was observed at A, B and C. The grain size at B is 61.3 μm and that of A is slightly larger than those of B and C. When the rotation speed increases to 50 $\text{r} \cdot \text{min}^{-1}$ and 150 $\text{r} \cdot \text{min}^{-1}$, the grain sizes at A, B and C decrease; and their dimensional relationship is $B < C < A$. The most significant refinement was obtained at B, which had average grain sizes of 40.2 μm and 38.2 μm under rotation speed of 50 $\text{r} \cdot \text{min}^{-1}$ and 150 $\text{r} \cdot \text{min}^{-1}$, respectively. Figure 9 shows grain size distribution at A, B and C of sample H4 at different rotation speeds.

During the solidification of centrifugal suction casting, alloy melt is fed through dendrite clearance to the casting. Movement of alloy liquid among dendrites is resisted so that feeding can only be realized with a certain amount of pressure difference. The pressure difference can be expressed as: \cite{9, 10}

$$\Delta p_i = \frac{1}{2} \rho \omega^2 (r_j^2 - r_i^2) + 2 \rho v \omega (r_j - r_i) + p_0 - \rho g (h_j - h_i)$$  \hspace{1cm} (1)

where $\rho$ is aluminum alloy density, $\omega$ is rotation speed, $r_j$ is centrifugal rotation radius in unit $j$, $r_i$ is centrifugal radius in unit $i$, $v_i$ is speed of the melt particle in position $i$ and $j$, $g$ is acceleration of gravity, $p_0$ is suction casting force, $h_j$ is the height of the unit $j$, $h_i$ is the height of the unit $i$. 

Fig. 5: Inner sinking face in tensile bars

Fig. 6: As-cast microstructure of horizontal specimen under 0 $\text{r} \cdot \text{min}^{-1}$ rotation speed

(a) at location A  (b) at location B  (c) at location C

Fig. 7: As-cast microstructure of horizontal specimen under 50 $\text{r} \cdot \text{min}^{-1}$ rotation speed

(a) at location A  (b) at location B  (c) at location C

Fig. 8: As-cast microstructure of horizontal specimen under 150 $\text{r} \cdot \text{min}^{-1}$ rotation speed

(a) at location A  (b) at location B  (c) at location C
There are three terms in the equation (1). The first is centrifugal pressure, the second is Coriolis pressure and the third is pressure difference produced by suction casting. It can be concluded from the equation that during the solidification process of suction casting, the feed pressure exerted on the melt is dramatically greater than the pressure of vacuum suction alone, due to the combined effects of centrifugal, Coriolis, and vacuum suctional forces. Therefore the feeding flux of the melt increases under centrifugal suction casting condition, compared to suction casting condition alone. Increasing the feeding flux gives rise to a decrease of defect volume and a densification of structure.

In the experiment, alloy flux at location C has the longest flow path with the greatest heat loss and the lowest temperature; therefore it is the cold end of the casting. Alloy flux at location A keeps the highest temperature; hence it is the hot end. When rotation speed is zero, only the vacuum suction force is exerted on the sample during solidification feeding. At locations B and C, the grain sizes are smaller than those at A; because B and C are more distant from the sprue than A; which leads to a lower temperature of the melt after mold filling, and a higher cooling rate. At rotation speeds of 50 r·min\(^{-1}\) and 150 r·min\(^{-1}\), centrifugal force is applied, in addition to the vacuum suction force. Alloy liquid rotates around the axis of rotation before solidification and causes mechanical vibration which leads to an increase of dendrites within the liquid metal. Dendrite growth is suppressed so grain size is smaller compared to the sample without rotation.

At location C the rotation radius is the largest, therefore the greatest centrifugal and Coriolis forces are exerted according to equation (1). Along with a lower temperature and a higher cooling rate of the alloy melt and the feeding gained during solidification, the grain size becomes smaller. At location B, the middle sample, the rotation radius is smaller than that at location C which gives rise to less feeding. The cross sectional area at B is the smallest (a diameter of 6 mm) and the solidification and cooling rates are the highest. These result in the smallest grain size. At location A the centrifugal force and feeding are the least; also this is near the sprue where the temperature is high and solidification rate is low. These result in the largest grain size. It can be seen from Fig. 9 that when the centrifugal radii are the same, grain size becomes smaller as the rotation speed rises, due to higher centrifugal force and hence a greater feeding effect at greater speed.

2.3 Influences of process parameters on mechanical properties

After T6 heat treatment, the cast specimens were subjected to room temperature tensile test. For each group, at least three samples were selected and the average tensile strength and elongation of the specimens were calculated. Figure 10 (a and b) shows the effect of rotational speed on tensile strength and elongation of horizontal specimens. When the rotation speed is 0, the differences in tensile strength and elongation of the four groups are not large. The transverse samples H1 and H2 can get a full feeding as they are close to the feeding channel; their performances are slightly better than the other two. After the application of the centrifugal speed, the tensile strength and elongation of the samples has been significantly improved. For one transverse sample, whose speed is 150 r·min\(^{-1}\), the tensile strength reaches 315 MPa and the elongation reaches 9.4%. These were higher by 11.2% and 38.8% than the VSC samples in the same location. This is mainly due to the centrifugal force and the feeding direction being in the same direction. This improves the feeding ability of casting solidification, make the cast metal more compact, and improves the mechanical properties. In addition, since the transverse H1 and H2 are close to the feeding
channel, these samples obtain better mechanical properties because of higher temperature, more time on solidification, a longer duration of centrifugal force, and a better feeding.

Figure 10 (c and d) shows the effect of rotational speed on the tensile strength and elongation of vertical specimens. When the rotation speed is 0, the differences in results for the vertical test bars in three groups on the tensile strength and elongation were not large. When the rotation speed is 50 r·min$^{-1}$, the tensile strength and elongation are greatly increased, and show an increase with an increase in rotation radius. This is because the larger the radius, the larger the centrifugal force, and the greater the feeding force. But when the rotation speed is increased to 150 r·min$^{-1}$, the centrifugal force increases, the free surface of liquid metal mold sprue is reduced, the hollow phenomenon appears. The vertical sample V1 is not completely filled, leading to gaps, bubbles and other defects and the casting becomes scrap. This will also make the tensile strength and elongation of vertical samples V2 and V3 under 150 r·min$^{-1}$ less than vertical samples under 50 r·min$^{-1}$.

For both horizontal and vertical samples, there is a big difference in solidification feeding in different casting locations due to the centrifugal force. Thus it has an effect on the properties of castings. Because the centrifugal force direction is horizontal, the horizontal samples get enough molten metal for feeding which gives the horizontal samples a better effect on solidification feeding. Therefore, when using C3 method to produce precision casting, the position of the casting has a significant impact on the final performance of the castings.

2.4 Effect of process parameters on density and hardness

By density test on samples at different speeds near the H4 samples, it is shown that the density with speeds 0, 50, and 150 r·min$^{-1}$ were 2.722 g·cm$^{-3}$, 2.894 g·cm$^{-3}$ and 2.923 g·cm$^{-3}$, respectively. Due to the centrifugal force, the 50 r·min$^{-1}$ sample density is 6.3% higher than the VSC samples, and the 150 r·min$^{-1}$ sample density is 7.4% higher than the VSC samples. Equation (1) shows that, under the centrifugal force field, the greater the rotation speed, the greater the centrifugal and Coriolis forces, solidification feeding capacity will be better during solidification, there will be fewer shrinkage defects and the casting is more dense.

Figure 11 shows the hardness values for different speeds at different locations of the H4 sample. When the speed is 0
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r·min$^{-1}$, the hardness values at locations A, B, C are substantially the same, their average value is 66.4 HV. When the speed is 50 r·min$^{-1}$, the hardness values at locations A, B, C have the features of $A < B < C$. But for the speed of 150 r·min$^{-1}$, the hardness of A, B, C show a significant difference. For location C, the temperature of the liquid metal is the lowest and it has the maximum feeding force, and has the continued feeding during solidification by the available gating system. It has fine equiaxed grain, so it has the highest hardness values, and the higher the speed, the higher the hardness value. Location A has the minimum solidification feeding force, and the greater the speed, the greater the influence of the metal free surface; so location A has the minimum hardness value and when the speed is increased, the hardness value is reduced. As the sample at location B is located between A and C, the difference is not obvious. Based on the above reasons, the centrifugal suction casting tests show that, with the increase of centrifugal radius, the hardness and mechanical properties are improved.

3 Conclusions

(1) Compared with VSC, the C3 cast alloy under both centrifugal and suction forces has better filling ability and strong solidification feeding ability. Due to the centrifugal rotation, the mechanical vibration and the enhanced ability of molten metal in the convection effectively inhibiting the growth of dendrites, the solidification is more uniform and the grains are finer. Centrifugal speed and centrifugal radius have a great influence on the solidification grain size, viz., under the solidification feeding channel, the greater the speed and the greater the centrifugal radius, the smaller the grain size.

(2) Compared with VSC, C3 can significantly improve the mechanical properties, density and hardness of castings. When the speed is at 150 r·min$^{-1}$, the maximum tensile strength is 315 MPa and the maximum elongation is 9.3%, increasing by 11.2% and 38.8%, respectively, compared to vacuum suction casting specimens. The radius of rotation and the rotation speed have a great influence on the density and hardness of the casting.

(3) For horizontal placement test bars, the mechanical properties are superior to upright test bars due to the centrifugal force and solidification feeding in the same direction. This greatly promotes the casting solidification feeding and reduces shrinkage defects, increasing the density of the casting.

(4) When the centrifuge rotor speed is too large, it is easy to produce casting defects in the casting interior. When the rotation speed increases to 150 r·min$^{-1}$, the free surface of liquid metal is too low, producing shrinkage defects in castings near the rotation axis, and reducing the mechanical properties.

References


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