Experimental and simulation study for rewelding defects during the flow process of Semi-solid die casting

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Abstract. Semi-solid die casting process due to its advantages of compact process, high performance and low cost is widely applied in automobile, communication and other industries for the preparation with high performance aluminum alloy castings. Compared with liquid metal melt, the filling behavior is laminar flow for semi-solid metal melt with higher apparent viscosity. In the process of semi-solid die casting, the semi-solid metal melt from different directions came together, it will lead to "rewelding" defects if with insufficient fusion or uneven slurry state. In this paper, the formation reasons and forms of flow "rewelding" defects are analyzed. By numerical simulation and experimental analysis, the flow state of semi-solid metal melt at the junction of filling frontier is represented, and the state of "rewelding" defect is characterized. The effect of eliminating defects is analyzed by modifying the mold structure, such as redesigning overflow and venting systems at the confluence position. The results show that the microstructure of the "rewelding" defects in the confluence position of the semi-solid metal melts is the segregation of solid and liquid phase, gas, oxidation inclusions and other defects. Different semi-solid die casting process will affect the flow state and defect size at the location of different semi-solid metal melt coming together. By means of the process control and the mold structure optimization, "rewelding " defects can be removed from the product cavity. The aluminum alloy semi-solid die-casting products with high performance are obtained finally.

1. Introduction
Semi solid metal (SSM) die casting technology has attracted widely attention to its industrial applications in aluminium alloy high-strength structures and sealing parts. It has been developed rapidly over the past decades. Compared with conventional die casting process, SSM die casting has completely distinctions on SSM slurry condition and filling behavior.

Because that in the traditional liquid die casting filling process, the liquid metal melt was sprayed with a large amount of gas with higher temperature above the liquid phase line, which can usually be combined after rewelding, and the requirements of die casting product is low of the mechanical properties, so such defects of rewelding do not need to pay much attention [1,2]. However, in semi-solid die casting process, the control of reweld defects is particularly important because of its high mechanical properties requirement.

Due to the geometry of the product, the semi-solid metal melt must be separated filling in the mold, and the metal passed through a certain distance and then came together, as shown in figure 1 [3]. This process of separation and recombination is called rewelding. In the semi-solid die casting process, the semi-solid metal melt filled the cavities from different directions with lower temperature, and if the flow of semi-solid metal melt is out of control, the rewelding quality of the casting is poor. In fact, most of the complex shapes of castings always have large numbers of rewelding. Therefore, the quality of the
rewelding in the semi-solid die casting process has an important influence on the performance of the casting.

![Figure 1](image1)

**Figure 1.** Some geometries of rewelding [3]: a is a confluence diagram; b is a plane confluence; c is an arc confluence

The welding behavior of semi-solid metal melts may be happened in several cases [4-6]:

1. The different semi-solid metal melts are not in contact;
2. The SSM melts are in contact, but the joint has no intensity or less strength;
3. The SSM melts are fused, and the joint has the same intensity as the matrix metal, no defects, and the partial air entrapments or oxide inclusions are exhausted out of the product.

2. Experimental procedures and analysis of die design for reweld mold

To study the rewelding quality of semi-solid slurry and its influencing factors during the die-casting process, the experimental mold was developed, as shown in figure 2. The combination of numerical simulation and experimental research was used to analyze the flow conditions of SSM melt, the influence factors of the overflow and venting on the rewelding quality with different the mold structures, and the key process parameters of different semi-solid die-casting (the mold temperature, ingate velocity and intensification pressure) on the rewelding quality of the casting.

![Figure 2](image2)

**Figure 2.** Experimental mold for researching the influencing factors of rewelding:
a no overflow and venting; b with overflow and venting;

3. Die design influence of overflow and venting on reweld quality

Semi solid die casting experiments were carried out in molds with overflow and venting, molds just with venting in the end, and molds without overflow and venting, by observing the rewelding conditions of the castings at the junction. Change to determine the effect of the overflow and venting on the quality of the rewelding area. The experimental parameters are shown in Table 1.

| No. | Fraction solid | Mold temperature/°C | Ingate velocity/(m/s) | Intensification pressure/MPa | With overflow and venting or not |
|-----|----------------|----------------------|-----------------------|-----------------------------|---------------------------------|
| A   | 0.45           | 260                  | 1.8                   | 80                          | None                            |
| B   | 0.45           | 260                  | 1.8                   | 80                          | Just venting                    |
| C   | 0.45           | 260                  | 1.8                   | 80                          | Both                            |
The semi solid die casting test was carried out according to the three groups of experimental parameters shown in the above table. Each group of experiments was repeated three times to observe the rewelding condition and microstructure of the rewelding area. The results are shown in figure 3.

![Figure 3. Effect of overflow and venting on rewelding: a is without overflow or venting; b is with venting without overflow; c is with overflow and venting](image)

As can be seen from the above figures, the overflow and venting have a great influence on the rewelding quality. In the macroscopic view, there are no visible reweld defects in the castings with overflow and venting. Significant reweld defects exist which can be clearly observed in castings without overflow or venting channel, but non-vented castings are more serious. Observing the microstructure of the three castings, it can be seen that there are no obvious reweld defects at the end of the castings with overflow and vent; there are obvious gas defects in the casting without overflow but with venting; Severe air entrapment is formed in castings without overflow or venting channel.

In the mold without overflow or venting channel, on the one hand, since there is no venting channel, the gas in the mold cavity cannot be discharged, and the back pressure is easily higher in the cavity, to air entrapment defects. On the other hand, the two SSM melts was filled with air entrainments from different location at the frontier of the slurry at the time of welding. Since the mold did not have an overflow, the slurry entrapped in the gas cannot be discharged and can only be solidified at the rewelding location. Therefore, the quality of the rewelding of the SSM slurry is poor.

In the mold without overflow but with venting channel, the gas in the mold cavity can be discharged through the venting channel. However, when the SSM melt was filling, the front edge of the slurry may be entrained, because the mold did not have overflow. Therefore, the quality of the rewelding of the slurry is poor.

In the mold with overflow and venting channel, the gas in the mold cavity can be discharged through these two structures. It can be seen from the above results that the overflow and venting channel have a great influence on the rewelding quality, and the rewelding quality of the slurry with the overflow and venting at the weld location is better.

4. The influence analysis of reweld quality by different semi-solid die casting parameters

4.1. Effect of mold temperature on reweld quality
The effect of mold temperature on rewelding was investigated. The experimental parameters are shown in Table 2.

The die casting test was carried out according to the No.1 to No.4 of experimental parameters shown in the above table. Each set of experiments was repeated 3 times to observe the welding condition and microstructure of the rewelding zone. The results are shown in figure 4.
Table 2. Experimental parameters of mold temperature on welding

| No. | Mold temperature/°C | Ingate velocity/(m/s) | Intensification pressure/MPa |
|-----|----------------------|------------------------|-----------------------------|
| 1   | 70                   |                        |                             |
| 2   | 175                  |                        |                             |
| 3   | 211                  | 1.8                    | 30                          |
| 4   | 279                  |                        |                             |

Figure 4. Effect of mold temperature on weld quality: mold temperature is 70 °C in a; mold temperature is 175 °C in b; mold temperature is 211 °C in c; mold temperature is 279 °C in d.

Figure 5. Simulation results of SSM slurry flow at different mold temperatures: a mold temperature is 100 °C; b mold temperature is 200 °C; c mold temperature is 300 °C.

As can be seen from figure 4, as the mold temperature increases, the quality of the rewelding joint is getting better and better. When the mold temperature is low (70°C), the macroscopically behaved as "through" continuous cracks at the rewelding line, and the microstructure showed the isolated state, with the poor rewelding quality. When the mold temperature is high (175°C and 211°C), the macroscopic behaved as "non-penetrating" intermittent cracks at the rewelding line. In the microstructure, there are many gas defects at the rewelding zone, and the rewelding quality is poor. When the mold temperature is high (279°C), there is no obvious rewelding defects in the macroscopic casting at the rewelding zone, and there is no obvious defect in the microstructure, and the welding quality is very good.

The flow of the slurry at different mold temperatures was simulated by Pro-CAST software and the results are shown in figure 5. In the figure, a is the flow state and temperature distribution of the slurry...
at a mold temperature of 100°C, b is a flow state and temperature distribution of the slurry at a mold temperature of 200°C, and c is a flow state and temperature distribution of the slurry at a mold temperature of 300°C. As can be seen from Figure 5, the temperature of the slurry flow front was increased as the mold temperature increasing.

When the mold temperature is low, the overflow of mold was not filled, and the slurry with poor quality of the front edge of the fluid (with air entrapment, oxide inclusions, etc.) failed to be discharged into the overflow, so that the rewelding quality was poor. On the other hand, when the mold temperature is low, the rewelding mode of the slurry at the location of joining may be "inverted V" type rewelding, and the gas in the mold cavity is not easily discharged, resisting the rewelding of the slurry. As can be seen from Figure 5, when the mold temperature is low, the temperature of the slurry front is low, and the exchange and penetration between the slurry are more difficult when the slurry was combined, so that the slurry is not easily integrated into one. Therefore, when the mold temperature is low, the quality of the rewelding joint of the slurry is poor.

Compared with the lower mold temperature, when the mold temperature is high, the overflow of the mold is filled, and the slurry with poor fluid front quality (with air entrapment, oxide inclusions, etc.) can be discharged into the overflow at the time of welding. The quality is getting better. On the other hand, the rewelding mode of the slurry at the time of joining may be a "V" type bonding, the gas in the mold cavity is easily discharged, and the rewelding quality of the slurry becomes good. As can be seen from Figure 5, when the mold temperature is high, the temperature of the slurry front is high, and when the slurry is combined, the frontier exchange and penetration between the slurry are more sufficient, so that the slurry is easily integrated into one. Therefore, when the mold temperature is high, the rewelding quality of the slurry is good.

5. Effect of ingate velocity on reweld quality

According to four experimental parameters shown in the below Table 1.3, the effects of different ingate velocities on the quality of the rewelding were investigated. Each number of experiments was repeated 3 times to observe the rewelding and microstructure of the joint zone. The results are shown in Figure 6.

| No. | Mold temperature/°C | Ingate velocity/(m/s) | Intensification pressure/MPa |
|-----|----------------------|------------------------|-----------------------------|
| 1   | 280                  | 0.6                    |                             |
| 2   |                      | 1.2                    |                             |
| 3   |                      | 3                      | 30                          |
| 4   |                      | 6                      |                             |

Figure 6. Effect of ingate velocity on rewelding quality: a ingate velocity of 0.6 m/s; b ingate velocity of 1.2 m/s; c ingate velocity of 3 m/s; d ingate velocity is 6m/s
It can be seen from figure 6 that as the velocity of the ingate increases gradually, when the velocity reaches a certain value, the rewelding defects visible to the naked eye appearing at the joint location. When the ingate velocity is ≤1.2m/s, the casting has no obvious rewelding defects on the macroscopic view, and there are no obvious defects in the microstructure, and the rewelding quality is very good. When the ingate velocity is 3m/s, the casting has no obvious weld defects on the macroscopic surface, and there are slight gas defects on the microstructure, and the quality of the rewelding was decreased. When the gate speed reaches 6 m/s, the casting has macroscopic weld defects visible to the naked eye, and there are large air entrapment defects in the microstructure.

![Figure 7](image1.png)

Figure 7. Simulation results of slurry flow at different injecting speeds: the ingate velocity in a is 0.6m/s; the ingate velocity in b is 3m/s; the ingate velocity in c is 6m/s

The flow condition and temperature distribution of the SSM slurry with different ingate velocities was simulated by Pro-CAST software. As can be seen from the results in figure 7, when the ingate velocity increasing, the temperature of the slurry flow at the junction is higher. When the slurry is at the junction, the temperature at the joint edge is high, and the exchange and penetration between the slurry are more sufficient, so that the slurry is easily integrated into one body, and the quality of the rewelding of the slurry is improved. However, as can be seen from the results of figure 7, when the ingate velocity is 6 m/s, the casting has macroscopic rewelding defects which is visible to the naked eye. This may be related to the way the slurry is combined at the junction, so the partial filling experiment is performed at different ingate velocities, as shown in figure 8.

![Figure 8](image2.png)

Figure 8. Partial fill type of different ingate velocity: the velocity of the ingate in a is 1.2m/s, and the velocity of the ingate in b is 6m/s

Figure 8 shows the partial filling of the velocity of different ingates, the ingate velocity is 1.2m/s in a, and the ingate velocity in b is 6m/s. From the results of figure 8, when the ingate velocity is 1.2m/s, the bonding mode of the slurry at the confluence is "V" type bonding; as the ingate velocity increases, when the velocity of the ingate is 6m/s, the combination of the slurry at the confluence is the 'inverted V' type combination. That is to say, when the ingate velocity increases, the slurry will have a "reverse V" type combination at the time of confluence location, which will make the gas in the cavity is not easy
to be discharged, and a certain air pressure is formed in the cavity to prevent the combination of the slurry, so that the quality of the rewelding is deteriorated. Therefore, as the velocity of the gate increases, the quality of the rewelding of the slurry deteriorates.

6. Summary
The following conclusions were obtained from the results of the simulation and SSM die casting experiment of reweld defects tests by experimental mold.
1. The overflow and venting channel have a serious impact on the quality of the rewelding, and the rewelding quality of the castings with overflow and venting is obviously better.
2. When the mold temperature rising, the temperature of the slurry at the junction is higher, the contact fusion between the slurries is easier to carry out, and the quality of the rewelding joint of the slurry tends to be better.
3. The velocity of the ingate is increased, and the quality of the rewelding joint of the slurry is deteriorating.

Acknowledgement
The research was carried out with financial support from the National Key Research and Development Program of China (N0.2016YFB0301001) and Shenzhen Science and Technology Innovation Commission under project (No. JCYJ20170307110223452 and No. KQJSCX20170328155402991) is gratefully acknowledged.

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