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Mold-Filling Characteristics of AZ91 Magnesium Alloy in the Low-Pressure Expendable Pattern Casting Process

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The magnesium (Mg) alloy low-pressure expendable pattern casting (EPC) process is a newly developed casting technique combining the advantages of both EPC and low-pressure casting. In this article, metal filling and the effect of the flow quantity of inert gas on the filling rate in the low-pressure EPC process are investigated. The results showed that the molten Mg alloy filled the mold cavity with a convex front laminar flow and the metal-filling rate increased significantly with increasing flow quantity when flow quantity was below a critical value. However, once the flow quantity exceeded a critical value, the filling rate increased slightly. The influence of the flow quantity of inert gas on melt-filling rate reveals that the mold fill is controlled by flow quantity for a lower filling rate, and, subsequently, controlled by the evaporation of polystyrene and the evaporation products for higher metal velocity. Meanwhile, the experimental results showed that the melt-filling rate significantly affected the flow profile, and the filling procedure for the Mg alloy in the low-pressure EPC process. A slower melt-filling rate could lead to misrun defects, whereas a higher filling rate results in folds, blisters, and porosity. The optimized filling rate with Mg alloy casting is 140 to 170 mm/s in low-pressure EPC.

Keywords expandable pattern casting, low-pressure casting, magnesium alloy

1. Introduction

The past ten years have seen a dramatic increase in the production and utilization of magnesium (Mg) castings around the world. This is primarily driven by the demand in the automotive industry to increase vehicle fuel efficiency by using lighter materials (Ref 1). Due to the lower density, high strength-to-weight ratio, high modulus, superior damping characteristics, good machinability, and availability, Mg alloys have been considered a desirable alternative to aluminum and steel for the production of lightweight components (Ref 2).

Mg alloys are produced mainly via sand casting, permanent mold casting, low-pressure die-casting, and high-pressure die-casting processes (Ref 3-5). The Mg products from sand casting primarily serve the military and aerospace industries. The high-pressure die-casting process is generally used to produce the Mg components with relatively simple geometries and lower mechanical properties. As the Mg alloy market continues to expand in the coming years, it will be essential to develop alternative casting methods that can be used to produce Mg castings with complicated geometries and superior mechanical properties than is possible using either high-pressure die-casting or sand casting (Ref 6).

The expendable pattern casting (EPC) process has now been developed into a well-understood manufacturing technology, and it is currently recognized as a viable option to the conventional Mg casting processes used to produce near-net shape castings of high quality and integrity (Ref 7-10). The EPC process is capable of making low-cost, complicated shapes by consolidating several components that are usually fabricated in conventional casting processes into a single part. Therefore, the combination of these advantages with the light weight of Mg can extend the application for Mg castings.

The low-pressure EPC process is a new precision method of making castings that has the advantages of the EPC and low-pressure processes. In this approach, the molten Mg alloy fills the mold cavity under a low pressure in a countergravity manner, forming a laminar flow profile. This reduces the exposure time of the molten Mg in air and overcomes the usual fill problems for a Mg melt in the conventional EPC process as a result of its excellent thermal conductivity and low latent heat.

As a newly developed casting process, little guidance has been described for foundrymen. Meanwhile, the most important initiative for the development of such a process is the improvement of mold filling during casting, from which it is expected to significantly reduce the casting defects. Producing Mg alloy castings using a low-pressure EPC process also has the advantage of easy automation, leading to labor savings. In addition, it is hoped that this approach will lead to better casting quality and higher yields. Therefore, this article has studied melt-filling rate and flow profiles using an AZ91 Mg alloy.

2. Experimental Procedure

2.1 Experimental Equipment

The low-pressure EPC process consists of two component systems: a low-pressure casting arrangement and the vacuum-sealed EPC process. A schematic diagram of the low-pressure EPC system is shown in Fig. 1. The low-pressure system includes a pressurized crucible and a feeding tube that can guide

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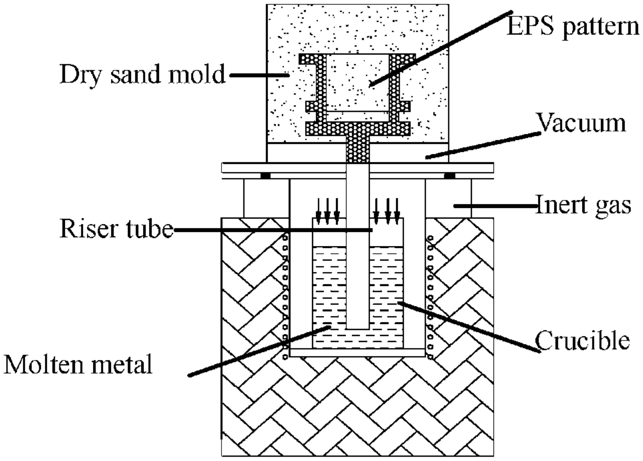

Fig. 1 A schematic diagram of the low-pressure EPC machine

the molten metal from the crucible to the bottom of the flask. When the appropriate pressure is applied to the surface of the molten metal in the crucible, it is forced to rise along the feeding tube and flow into the expendable pattern via the gating system, which has been well embedded with dry sand and a vacuum system. When the expendable pattern is fully replaced with molten metal, the pressure on the melt is further increased to reduce feeding shrinkage during solidification. The pressure is released after the casting has completely solidified. At this time, the molten metal in the riser and transfer tube is allowed to flow back into the crucible through the action of gravity.

2.2 Expendable Pattern

The experimental plate-casting pattern and its gating system were made from the most widely available expandable polystyrene (EPS) board. A hot wire cutter was used to cut the EPS to the necessary shapes for the pattern and gating. The bulk density of the EPS was 0.016 g/cm^3. In these tests, an L-shape and a rectangular shape plate pattern with a 5 mm thickness were prepared. The gate was directly cut with the plate pattern, so the cross section was 5 × 40 mm. The two patterns were connected directly to the horizontal runner (cross section 20 × 60 mm; length 180 mm). The sprue size was 46 × 80 mm. The cluster was rigged using commercial glue, as shown in Fig. 2. On one side of each pattern, 18 electrical probes were arranged to monitor the filling time of the melt front. Each probe gave an electrical signal once the molten alloy touched the tip of the probe.

2.3 Coating

The glued clusters were coated with a specially confected refractory slurry (Baume 45). The coated clusters were then put into an oven to dry for 4 h at 40 to 60 °C. The clusters were coated and dried additional times until the coating thickness reached 0.5 mm.

2.4 Molding, Melting, and Pouring

After the probes had been positioned on one side of the pattern and connected to the data-acquisition system, the coated patterns were placed into a top-open (ϕ 400 × 400 mm) steel flask with a plenum chamber on its base and subsequently were filled with dry silica sand (40/70 mesh) to enclose the coated pattern. The entire sand-mold assembly was then compacted using a three-dimensional compaction table. After the coated pattern was properly embedded, packed with dry sand, and compacted, a plastic film, 0.1 mm in thickness, was used to cover the open top of the flask.

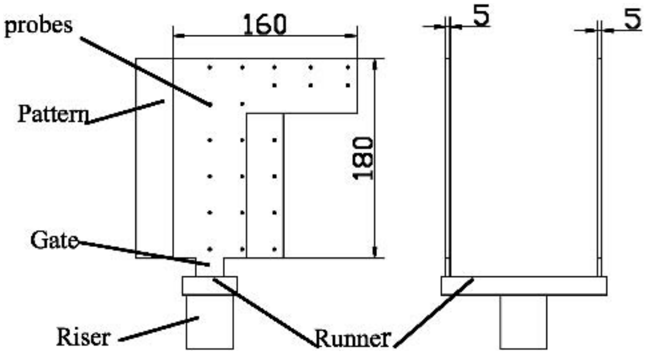

Fig. 2 The schematic diagram of the expendable pattern used in tests

AZ91 Mg alloy ingots were melted in the resistance furnace. The melt temperature was measured with a chromel-alumel thermocouple. When the alloy began to melt, a gas mixture of 0.2 to 0.5% sulfur hexafluoride (SF_6) in nitrogen was allowed to flow over the melt surface to protect the Mg alloy from oxidation and burning. Once the melt reached 730 °C, 0.5 wt.% of a grain refiner was added to the melt while continuously stirring for 5 to 8 min to achieve a uniform distribution. After allowing the melt to settle and deslagging it, the flask with coated the EPS pattern was positioned on the top of the furnace and the vacuum was applied to the flask to fix the dry sand. At this point, the mold-filling procedure was initiated through the use of the mold-filling control system.

3. Results and Discussion

The primary variable measured during the experiment was the filling time at different positions on the EPS pattern. Based on the experimental results, a diagram showing the melt front during mold filling was constructed, and the melt fill rate was calculated accordingly.

3.1 Mold-Filling Profile

Using the times at which the molten metal front contacted each probe, isochronal lines were used to construct metal fill profiles for the experimental castings. Figure 3 shows the shapes of the metal front at 0.5, 0.3, and 0.2 s intervals after the metal passed the gate of experimental castings.

Figure 3(a) shows the filling pattern of Mg alloy for a 1 m^3/h flow of inert gas in the low-pressure EPC process. It indicated that the metal/foam interface exhibited a smooth convex shape when the flow quantity of inert gas was less than 3 m^3/h. However, the molten Mg alloy filling the mold at this rate gave rise to misrun defects and incomplete filling.

As the flow quantity of inert gas increased, the driving force for mold filling increased. When the flow quantity of inert gas was $\geq$3 m^3/h, the liquid metal flowed into the mold in the form

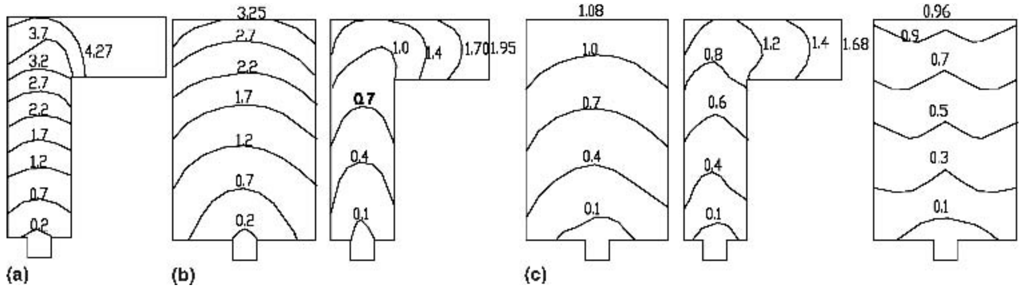

Fig. 3 Schematic diagram of the isochronal lines of molten Mg alloy. See text for description of (a) to (c).

of a convex or arrow shape, as shown in Fig. 3(b). The filling time of liquid metal was reduced greatly, and no misrun or other pyrolysis defects occurred internal or on the surface of plate castings.

If the flow quantity of inert gas was too high (i.e., 5 m^3/h), the metal front did not move smoothly, as shown in Fig. 3(c). A large number of fine pores was found at the inner and top end of the castings. This was not surprising, because the liquid metal front of the casting would be overloaded with liquid pyrolysis products just ahead of the metal front, particularly when the metal velocity is high and there is not sufficient time for the liquid polymer to be removed through the coating.

3.2 Influence of the Flow Quantity of Inert Gas on Metal Velocity

In the Mg alloy low-pressure EPC process, the driving force for melt filling comes mainly from the gas pressure. The overall gas pressure depends on the flow quantity of inert gas and is the principal processing parameter that influences the metal fill rate. The velocity of liquid Mg alloy was measured using several sets of probes that were prepositioned along the centerline of the plate casting. The results indicated that the metal velocity was greatly influenced by the flow quantity of inert gas, as shown in Fig. 4. The average melt fill velocity was slower for a low inert gas flow rate (i.e., <3 m^3/h). Misrun defects occurred at this flow rate. As the flow rate of inert gas increased (i.e., 3 m^3/h), the average metal fill velocity increased, and no defects internal to, and at the surface of, the rectangle and L-shape plate castings were discovered. However, when the flow quantity of inert gas was >3 m^3/h, the increase of metal velocity was not significant. The results suggest that the melt fill rate was controlled by the flow rate of inert gas for lower metal velocities, but the decomposition of polystyrene foam, and/or the transfer of decomposition products, controlled the metal fill rate at high metal velocities.

3.3 Changes of Metal Velocity During Mold Filling

The molten AZ91 Mg alloy filled the mold in a counter-gravity manner from the gate under increasing gas pressure in the low-pressure EPC process. The experimental results indicated that the molten Mg alloy did not fill the rectangular plate casting at a consistent velocity, and the fill rate decreased gradually during casting when the flow rate of inert gas was low (e.g., 1-2 m^3/h). These conditions resulted in the formation of misrun defects in the castings. As the flow rate of inert gas increased, the change of metal velocity tended to be steady, as shown in Fig. 5 and 6. For the L-shape casting, in addition to the above-mentioned metal fill behavior, molten metal filled the mold at a much slower rate due to the change in the flow pattern as it passed through the L-shaped junction between the vertical and horizontal plates.

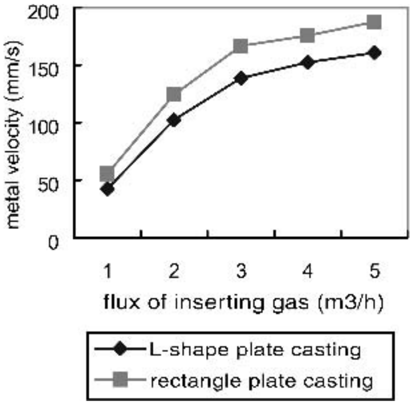

Fig. 4 The influence of the flow quantity of inert gas on the metal velocity

As shown in Fig. 5(a), the 90° intersection momentarily slowed the progress of the metal front. Most likely, the change in the velocity at the intersection was due to a fanning out of the metal front as it moved into the junction of the L-shaped plate, thus establishing a much larger metal-foam front. These results suggest that the metal velocity of the AZ91 Mg alloy is not consistent during the whole mold-filling process. The more complicated the shape of the casting, the greater the change would be in the metal velocity. The total filling time of the Mg alloy increases with the complexity of the casting.

4. Conclusions

This work confirms that the velocity and flow pattern of the metal front are associated with the formation of pyrolysis defects in AZ91 Mg alloy low-pressure EPCs. In this newly developed casting process, the velocity and the flow pattern of the melt are principally controlled by the flow rate of the inert gas. The results indicate that a low flow rate (i.e., <3 m^3/h) leads to

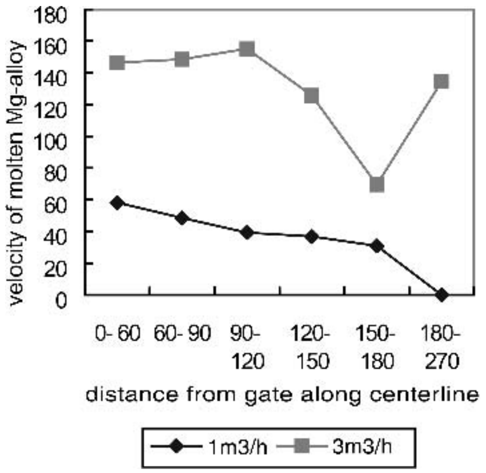

Fig. 5 The changes of metal velocity of L-shape plate casting

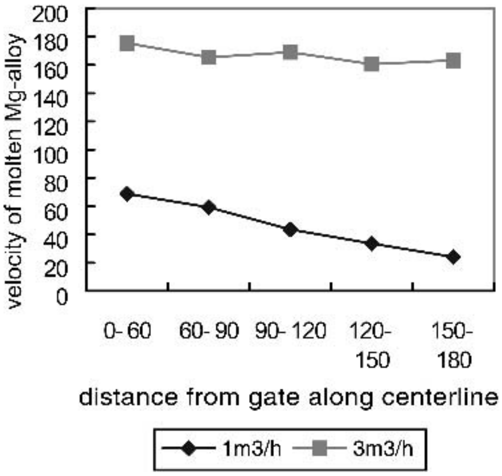

Fig. 6 The changes of metal velocity of rectangle plate casting

a slower melt velocity with a smooth convex melt front. However, misrun defects frequently occur. When the flow rate of inert gas is higher (i.e., >4 m^3/h), the metal velocity is also high, and this leads to an unstable melt front. These conditions also resulted in casting defects, including folds, blisters, and internal porosity. These defects occurred because there was insufficient time for the liquid pyrolysis products to transfer into, or through, the refractory coating. An optimized melt velocity was obtained when the flow rate of inert gas was controlled to between 3 and 4 m^3/h for the simple plate castings.

In addition, the changes in mold-filling velocity in the low-pressure EPC process suggests that the junction of casting could decrease the metal velocity, leading to an incomplete fill. Therefore, more complex Mg alloy castings may need higher flow rates of inert gas during low-pressure EPC.

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