Development of vacuum die-casting process

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Abstract: The vacuum die-casting process, started 25 years ago in Japan, has been widely applied. This technology contributes very much to improvement of castings quality. The main factor causing the defects of die castings is the trapped air in the mold cavity, while the key technology of vacuum die-casting process is to avoid the trapped air effectively by evacuating the cavity before casting. At the same time, due to the shot speed and the casting pressure reduced in half, the service life of the die is prolonged and the productivity is enhanced, as well. Vacuum die-casting process is of great significance in improving the die castings quality and making up the shortcomings of super-high-speed shot casting.

Key words: vacuum die-casting; die tooling; GF process

Vacuum die-casting process was introduced into mass production in 1983, after gas free (GF) process was invented. Around the same time, OPTI-VAC process was advocated in Europe, but it was not widely applied. On the other hand, GF process was introduced to all major die-casters and automobile makers in Japan and 52,690 tons of castings (7.7% of total yearly die-casting production) was cast in 1992 with this process. Soon after, GF process was introduced into European market and it became popular worldwide afterwards.

In these days, ultra-high-vacuum die-casting process has been developed in Europe and starts to be applied for producing large and thin parts, such as space-frames and pillars, which are usually welded to automobile chassis.

This report describes the mechanism of vacuum die-casting process, its development and applications.

1 Circumstances of developing GF process and its constitution

Major die-casting defects are blowhole, shrinkage, cold shut, flow line and misrun. Except for shrinkage, all other defects are associated with trapped air during feeding. This phenomenon had already been known and well-documented in 1980’s, empiricism suggested to evacuate air in die cavity for eliminating these defects. According to these practices, many vacuum processes were proposed, designed and tested, but none was suitable for mass production. The reason is explained using Fig.1.

The process starts with evacuation when position signal C is activated during low speed filling. The change of shot speed to high speed mode is completed by position signal B; once position signal A is activated, the shut off valve is closed near shot end to avoid melt aluminum entering into vacuum line. The challenges for such process are the control of pouring weight of aluminum and also the motion time of shut off valve. If discrepancy or delay happens during the process (computer technology was poor at that age and AC solenoid valve needs 8 ms error to be ON in the relay circuit), melt aluminum flows into vacuum line and this would halt production. It will take 30 minutes to 1 hour to remove the intruded aluminum.

GF process was invented in 1980 under the pressure of strong demand for more reliable shut off valve. Figure 2 shows GF process schematically. The whole process is similar to that shown in Fig.1, but the design for shut off valve is completely different. It closes passively using inertia force of metal flow without being affected by porting weight error or shot conditions. Such, the new vacuum process was established showing reliability and applicability for mass production.

2 Know-how to use GF process effectively

Practical usage and features of GF process is summarized as follows:

1. Vacuum time should be within 0.3 s (maximum 0.5 s). If pumping time (from vacuum start command C to high speed command B) is more than 0.5 s, the possibility of producing blowhole defect increases.

Coating spray must be applied to die surface to prevent...
Fig. 1 Layout of early developed vacuum process

Fig. 2 Schematic drawing of GF process
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adhesion of aluminum before casting. Almost all water-based solvent is vaporized by the heat of die and the solute makes the coating film at the die surface. But very few amount of liquid may intrude into the gaps between die and cores, and those liquid remain liquid especially in the case of die tooling with many slide cores. If die cavity is evacuated for more than 0.5 s, remaining liquid can be sucked into the cavity surface and vaporized rapidly when contacting the melt. The gas can be easily entrapped into the casting and form blowholes. Spray liquid is diluted over 40 times with water and the vaporized water inflates 1,240 times in volume. Concerns about water vapor inflation must be considered even very small amount of spray liquid is employed. It has been demonstrated that vacuum within 0.3 s is appropriate to prevent above-mentioned problem.

(2) Good vacuum system and well designed die tooling need no sealing at the parting line of die or slide cores. An optimum condition (without sealing) could be obtained by applying 20-27 kPa vacuum.

(3) Die tooling for ventilation should be designed to have enough evacuating ability as 20-27 kPa could be established within 0.3 s.

(4) Vent runner should be adopted at the final filling point determined by numerical metal flow analysis. One fifth of air still remains after evacuated to 20 kPa in the die cavity, so the remaining air should be pushed out by metal flow itself. Figure 3 shows examples of defects expected from inappropriate design of final filling point. Last remaining air could not be pushed out through air vent because it was already entrapped by melt. Modifying vent runner from side to bottom could remarkably reduce blowholes.

For design purpose, Fig. 4(a) shows an original die layout for a grill tray. This product is polished inside of tray portion after deburring and then applied PTFE coating with burning treatment. Blistering may occur at this treatment if blowholes exist at near surface of the casting. Figure 4(b) shows the first die layout for GF process with wrong vent runner design, as described previously. By moving the vent runner from side to bottom, Fig.4(c) shows the modified tooling and as a result, the production rejection rate has been reduced from 30% for the design of Fig. 4(a) to 0.5%. The numerical simulation with CAE is shown in Fig. 5, where the final filling points can be easily identified without further casting trials.
3 Characteristics of GF process

GF process has been recognized as an efficient die-casting process to eliminate defects, such as blowhole, cold shut, flow line and misrun. Like almost all other casting techniques, unexpected effects for GF process can also appear. That is, good parts can be obtained with lower shot speed and/or lower metal pressure. For instance, shot speed can be reduced from 2.5 m/s to 1.5 m/s, or metal pressure can be reduced from 80 MPa to 50 MPa without sacrificing casting quality. This is because excess power was needed to cancel back pressure of remaining gas in the cavity without GF process. At casting site, reduction of shot speed and metal pressure prevents burrs remarkably, and it also prolongs die life, eliminates deburring operation and increases up time of casting machine. In starting up new parts, good parts can be easily obtained with GF process so modification process of die tooling can be reduced, and totally new product can be introduced into mass production in a relatively short period of time.

But there are some disadvantages. One of them is that aluminum melt can intrude into vacuum line when aluminum dreg stuck at shutting valve sheet during last shot. The procedure of trouble-shooting of this problem is described in the next section.

4 Evolution of GF valve

Figure 6 shows a schematic of a mechanical type GF valve. Main valve is locked by ‘open lock ball’ that holds valve in open position against shut force of ‘shut spring’ and vacuum suction until melt front hits the valve. Open lock ball must be adjusted to loose against shut off force just before metal front. If locking force is weak, main valve shuts with vacuum force before melt comes to the valve portion. In this case, a large amount of air still remains in the cavity. On the other hand, valve does not shut at proper moment if locking force is strong and aluminum may intrude into the vacuum line. Therefore, it is critical, and also difficult, to adjust locking force of ‘open lock valve’. It has been suggested that the locking force is adjusted once a day with an exclusive jig.

Early GF valve adopts mechanical lock system (shown in Fig.6), the locking force reduces with time as the groove in main valve wears. Though there are screws behind open lock balls to adjust locking force, it is always a challenge to adjust two spring evenly. If this adjustment is not enough, shut off timing may be inaccurate and insufficient evacuation (shut off faster with too small locking force by groove wear) or aluminum intruding into the vacuum line and jam (shut off slower with too much locking force) may occur. It is also recommended that replacing valve set to a new one if there is a sign of jam-like error detected by electric signal. Valve unit looks like a cassette unit and can be replaced easily within 10 minutes. Some customers replace valve unit every 4 hours even if there is clear evidence of jam.

Further investigation on the collision force applied to the main valve indicates that jam might be caused by such collision force intermittently against supposition. This phenomena is so called “flying melt”, as indicated in Fig.6. If the vent runner is straight and short, jam can easily occur. Effective countermeasures to avoid jam are to make vent runner longer and add more than two of 90 degrees turns, this is illustrated in Fig.7.

Figure 7(a) shows the moment before GF valve opens. As air pressure is introduced into Room-A, the main valve is pushed downward and the piston touches O-ring. Under this condition, bring air pressure into Room-B continuously and exhaust air in Room-A, air pressure force in Room-B pushes the piston downward and keep the main valve open shown in Fig.7(b). Vacuum evacuation is done in this procedure.

Shot velocity shall be changed to high speed mode at the moment that vacuum pressure reaches the set value. Figure 7(c) shows the moment when main valve shuts off. If vacuum is high to increase the shot speed so that the front of the melt pushes the main valve hard and breaks the O-ring seal, the air could leak through the gap. Then air pressure starts to act on both upper and bottom sides of the piston, and upward force dominates because the effective cross section areas are different (Rod-A is thinner than Rod-B and bottom side area of the piston is larger than upper side). The main valve goes up and shuts vacuum line automatically.

Characteristics of this air-driven type GF valve is easy to adjust locking force by simply controlling air pressure.
introduced into Room-B. As a result, the locking force can be adjusted during continuous casting operation without using special jig. Since there is no mechanical lock, wear is almost negligible. Another feature of air-driven GF valve is its high sensitivity of starting shut off movement. In contrast to 0.6 mm valve lifting distance for mechanical type valve, only 0.2 mm lifting is required for air-driven type GF valve.

A recorded 92,000 shots run without a jam has been reported for air-driven GF valve. Many user add their own know-how into die tooling for stable production. Details of die tooling is beyond the scope of this paper. As a matter of fact, the GF valve has promoted die design in Japan. In the mean time, UBE, the inventor of GF valve, has been continuously investigating and adopting new designs and technologies to minimize jam problem. For example, more sensitive reaction against melt collision in starting vacuum evacuation can be achieved by changing operating sequence (i.e. reducing air pressure in Room-B, open-holding power, and then add pressure in Room-A).

5 Relationship between high-speed shot and vacuum die-casting

Effect of vacuum process was described in the previous sections. For a direct comparison, a same dimension of ADC12 plate (equivalent to AA383) was used (200 mm width, 270 mm height and 4 mm thick), the gate thickness was 2 mm, and a metal pressure 50 MPa was employed. The advantages of vacuum die-casting over high-speed shot casting are illustrated in Figs. 8 and 9. Figure 8 shows the change in density of castings as a function of shot velocity, produced by normal die-casting and GF ultra-high-vacuum process. It can be seen clearly from Fig. 8 that casting density using GF ultra-vacuum casting is consistently higher than those with normal die-casting. It is also noted that the density does drop with increasing the shot speed in both cases. Figure 9 shows gas content in the casting as a function of shot speed. Though the gas content in the casting using both processes increases with shot speed, GF vacuum casting dramatically reduces the gas level by almost one order of magnitude.

It has been found that blowhole defects seem to disappear with increasing shot velocity over 4 m/s, especially on the machined surface. However, entrapped gas still remains, and the small porosities became uniformly distributed and hardly seen with naked eyes. Small blowholes might cause leakage if linked together and/or blistering if PTFE coating is used. The comment “There is no need of vacuum process for ultra-high-speed die-casting” can only be said in the case of discussing defects on machined surfaces. It is believed that vacuum process is necessary to get high quality castings combined with
ultra-high speeds.

Data of vacuum process presented in Fig.8 and Fig.9 were made with GF ultra-vacuum process, which will be described in the next section. Usual GF process can also get such good data if desirable conditions, especially die tooling, are met. Casting produced under such conditions involves gas content of lower than 4 mL/100g Al, which is within the limit of castings for welding.

6 Ultra-high-vacuum die-casting process

Ultra-high-vacuum die-casting process was first proposed and designed in Europe around 1995 for producing large and thin automobile parts, such as pillars and space frames. These parts need to be welded so gas containing must be lower than 4 mL/100g Al. Ultra-vacuum as 5-10 kPa is generally achieved by sealing between dies and cores (sometimes at ejector pinhole) using O-ring and piston ring around plunger tip. In comparison, 20–27 kPa vacuum can be achieved in a normal GF process without any sealing.

Normal GF process evacuates die cavity to about 20 kPa with around one fifth of atmosphere remains. Therefore remnant gas must be pushed out through air venting slot by metal flow (with adjusting shot conditions). Die tooling having long flow length is not suitable for manufacturing large and thin castings because long metal flow reduces metal temperature, which in turn may cause defects like misrun or cold shut. By increasing the vacuum up to 5 kPa, remnant air is reduced to one twentieth of atmospheric pressure, so flow route can be minimized without considering exhausting air from venting slot. Schematic diagram of ultra-vacuum system with GF valve is shown in Fig.10. The system is almost same as normal GF system except for adding seals between dies and cores and piston ring around plunger tip.

With the improved design for ultra vacuum, evacuation time
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During casting becomes more important. It is better switching from slow speed to high speed within 0.5 s to prevent “flying metal” from overhanging on the distributor and being inspired by vacuum flow into the cavity, and this has to be changed after cavity pressure reaches target value.

Other featured changes for ultra-vacuum compared with the normal GF process are: (A) doubled flow capacity of vacuum switch valve and vacuum tank capacity; and (B) the location of the vacuum switch valve. The switch valve is used to locate on tank side with the vacuum pump as one unit to be portable easily, and is connected with GF valve by long hose. Refer to Fig.10, GF system has 5–7 m hose at part A and 0.5 m at part B. So the system must evacuate two to three times air in the hose than cavity volume. It is not an issue for normal vacuum as low as 20 kPa and it can be reached within 0.3 s. However, for ultra-high-vacuum as high as 5 kPa, the vacuum switch valve has to be moved to the top of the ejector side platen. Such the new system has 1 m hose at part A and 5–7 m at part B, and the hose at part B is also doubled in thickness. Combined with large exhaust volume of GF valve, this unit pumps fast vacuum as 5 kPa within 0.32 s. An overall comparison between conventional GF process and ultra-vacuum die-casting process is tabulated in Table 1.

7 Comparison of die tooling between GF process and ultra-high-vacuum die-casting process

As described in section 6, die tooling for normal and ultra-high-vacuum GF die-casting are different. Schematic drawings shown in Fig.11 explain basic concept of both processes. The keys for both processes are directional filling for normal GF vacuum die-casting and shortened flow length in ultra-high-vacuum, respectively.

| Table 1 Comparison of normal GF process and ultra-vacuum die-casting process |
|---------------------------------|---------------------------------|-----------------|----------------|
| Term                           | Normal GF process              | Ultra-high-vacuum |
|                                |                                | UBE GF process   | Others         |
| Vacuum pressure                | 20–27 kPa                      | 5–10 kPa         |                 |
| Time to be evacuated           | 0.3 s                          | 0.32 s           | 1.0–1.5 s       |
| Seals                          |                                  | O-ring           | O-ring          |
| Die parting                    |                                  |                  |                 |
| Core                           |                                  |                  |                 |
| Ejector pin                    |                                  |                  |                 |
| Plunger tip                    |                                  |                  |                 |
| Gas content in products        | 2–10 mL/100g Al                 | 2–4 mL/100g Al   |                 |
| Usage                          | General die-casting             | Pillar, sub-flame, node, bracket, upper-arm |

8 Summary

GF die-casting process was invented in 1983 and developed quickly into mass production field. With GF process, several vacuum processes were proposed. In 1995, ultra-high-vacuum process first appeared and several ultra-vacuum processes
were also developed in this decade. But application of these ultra-vacuum processes is limited in automobile body parts. All products are large and need huge sized die-casting machine like 2,500–4,000 tons of die clamping force, so these processes did not become popular among car makers and large diecasters. General die-cast parts do not need ultra-vacuum process. Normal vacuum process is good enough to eliminate defects except for shrinkages.

It is reported that the combination of ultra-high-vacuum and ultra-high-speed shot process can produce high quality castings having 8%–15% elongation with lower metal pressure. This indicates high quality castings may be produced with the casting machine now in use with further modifications. Technologies for ultra-vacuum process and multi-metal pressure (including low pressure) casting have become mature. It will be challenging for the machine maker to combine those technologies and make stable mass production at high shot velocity of 6–7m/s.

Recent automobile parts, especially safety suspension parts that need high strength or rigidity, are converted from ductile cast iron to heat-treated gravity aluminum casting, and then to heat-treated aluminum die-casting. In this case, the cast wall is as thick as 20–30 mm. To get lighter and thinner suspension parts, the tendency of transition from thick aluminum casting to lighter rib-structured thin aluminum casting becomes necessary. Such transition was already witnessed in Europe more than 10 years ago.

As described above, die-casting machine and casting process are now in progress to seek new technologies for the future. It is expected that vacuum casting process will play a major role in die-casting industry for both product quality and mass production efficiency.