

A new counter-gravity casting process, mold filling dynamics, convective heat transfer and influence on mechanical properties

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ABSTRACT

Technology of making near net shaped casting has been developing rapidly in recent decades of years with the drying up in metal resources and for the environment protection. Foundry is changing towards a precision metalworking technology. Precision or investment castings, usually also called lost wax castings, are characterized by thin-walled cross section, intricate shape and very little dimension tolerances. To shape the “thin-walled casting”, some counter-gravity processes, which utilize air pressure and electro-magnetic force, such as low-pressure casting, counter-pressure casting and vacuum-absorption processes, are being widely used in foundry industry. But some limitations and shortcomings appear when these processes are applied to thin-walled investment castings. Therefore, it has been the foundrymen’s persistent goal to find more effective technology. In the present paper, an innovative counter-gravity process (CAP process for short) is proposed on the overview of the present processes.

The characteristic of the mold filling under counter-gravity is that the molten metal is forced to fill mold cavity against gravity under the pressure difference and the casting solidifies under a determined pressure. The pressure difference is one between the pressure on the surface of the molten metal in the crucible and the pressure within the mold cavity ($P_2 - P_m$). Obviously, there is the following hydrostatic relation:

$$(P_2 - P_m) = \rho gh + L + V \quad (1)$$

where, ρ is density of the molten metal, g is gravity acceleration, and h is the height from surface level of the molten metal in the crucible to the top level of the filling front; L is Laplace force, depending on the wall thickness of the casting and the surface tension between molten metal and the molding materials; V is the viscosity force; it has something to do with the physical properties of the metal and temperature.

The pressure difference ($P_2 - P_m$) can be created by the following three methods:

1. Making the upper chamber negative pressure at the same time maintaining the lower chamber at atmosphere, which is also called vacuum absorption. For example, the famous CLA process depends on this principle).
2. Making the lower chamber positive pressure at the same time maintaining the upper chamber at atmosphere. The widely used “low pressure die casting” depends on this principle. In fact, for low-pressure casting, no upper chamber is needed.
3. Making pressures within upper and lower chambers increase simultaneously to a determined value, and then making upper pressure reduce at the same time maintaining the lower pressure

unchanged, just like CLA process, which is called “ counter-pressure casting” by Bulgarian. From the equation 1, not taking L, V into consideration, we have:

$$\left(\frac{dP_2}{dt} - \frac{dP_m}{dt}\right) = \rho g \frac{dh}{dt} \quad (2)$$

where, t is mold filling time. So dh/dt can be thought as mold filling velocity. It can be seen from equation 2 that the mold filling velocity mainly depends upon the ratio of pressure difference to the filling time, $d(P_2 - P_m) / dt$. For vacuum absorption and counter-pressure castings, $P_2 = \text{Const}$, so the equation 2 can be written as:

$$-\frac{dP_m}{dt} = \rho g \frac{dh}{dt} \quad (3)$$

The equation 3 shows that mold filling relies on the change of pressure within mold cavity P_m , that is to say, relies on the permeability of the mold because we control P_m by controlling P_1 . If the mold is complete permeable to air, then $P_1 = P_m$, so the mold filling can be controlled accurately. Otherwise, the castings are subjected to cold shut and misrun. Similarly, the low-pressure process works the same way. The mold filling process is substantially a process that the molten metal replaces the air within mold cavity. In fact, for investment casting, the mold permeability is usually very poor. So it is difficult for air to escape from the mold cavity during mold filling and the air will be compressed to a high pressure, also called backpressure, against mold filling. The backpressure, which is created during mold filling under low pressure, has a significant influence on the dynamics of mold filling. In fact, the backpressure is usually an uncontrollable parameter. Generally speaking, no vent holes are set in mold shell for investment casting in real practice, so when controlling the P_1 or P_2 , one don't know real value of P_m and so the mold filling is difficult to control.

CAP process can be divided into 5 stages, that is,

1-making vacuum in the upper and lower chambers simultaneously. Because the mold cavity is made wholly permeable through a specially designed mechanism, so it is in the same degree of vacuum as the upper chamber. No pressure difference is created, so the liquid metal within the crucible is static;

2- the liquid aluminum is forced to flow up into the mold cavity through a feed tube against gravity under pressure at determined pressuring rate until the mold cavity is completely filled;

3- increasing the pressures rapidly simultaneously within upper and lower chambers with the pressure difference between upper and lower chambers maintaining constant;

4- maintaining a stable pressures until the solidification of the casting completed and

5- connecting through the upper and lower chambers to eliminate the pressure difference, or pressure balance. As soon as the pressure difference is eliminated the unsolidified metal in the sprue and feed tube will flow down to the crucible below.

The purpose of vacuum prior to the mold filling is to evacuate the air in the mold cavity, at the same time, degassing the molten aluminum so that the hydrogen dissolved in the metal can escape in the form of bubbles. This procedure is also called vacuum refining.

Obviously, from equation 2, if P_m is close to 0, then we have:

$$\frac{dP_2}{dt} = \rho g \frac{dh}{dt} \quad (4)$$

It is clear that mold filling can be controlled with high accuracy due to eliminating the effect of the backpressure within the mold cavity. The mold-filling rate depends only upon designed pressure function P_2 . For example, the function can be linear or exponential according to the task requirements.

It is important that the solidification must proceed under positive pressure because the hydrogen is easier to separate out from the molten aluminum under negative pressure to result in micro porosity and pinholes in the casting.

According to the hydrogen solute balance in the molten aluminum, it has:

$$P_g = \left[\frac{C_0}{k_s f_s(t) + k_l (1 - f_s(t))} \right]^2 \quad (5)$$

It can be seen from equation 5 that the separating-out pressure of the hydrogen is proportional to the square of the initial hydrogen content C_0 , and increase as solidification proceeds, or $f_s(t)$ increases. Therefore, even if a trace of hydrogen is present in the molten aluminum, the separating-out pressure will get to very high value as the solidification proceeds to the final stage. In this case, the pressure exerted on the casting P_2 should be much larger than P_g , that is to say, the ambient pressure should change rapidly from negative (close to vacuum) to positive and complies with the following condition:

$$P_2 > P_g \quad (6)$$

To increase pressure P_2 , the common usage is to increase the pressure on the surface of the molten in the crucible that is placed in the lower chamber, with the upper chamber still vacuum. But in this way, the pressure difference between the upper and lower chamber will increase large enough to make the mold shell deform and even crack. That is very dangerous situation. Therefore, the pressures within both upper and lower chambers should follow the relation:

$$\frac{dp_1}{dt} = \frac{dp_2}{dt} \quad (7)$$

That means the pressure curves of upper and lower chambers should maintain parallel during pressure adjusting to guarantee the minimum load exerting on the mold shell.

The experiments were carried out to validate the process. The heat transfer condition was discussed and mechanical properties were compared between gravity casting and CAP process.

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