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Development of an interactive simulation system for the determination of the pressure–time relationship during the filling in a low pressure casting process

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Abstract

An interactive computer simulation system has been developed in this study to aid the determination of the pressure–time relationship during the filling of a low pressure casting to eliminate filling-related defects while maintaining its productivity. The pressure required to fill a casting in a low pressure casting process can be separated into two stages. The first stage is to exert pressure to force the molten metal to rise in the riser tube up to the gate of the casting die, which varies from casting to casting due to the drop of the level of the molten metal in the furnace, whilst the second stage is to add an additional pressure to push the molten metal into the die cavity in a way that will not cause much turbulence and have the proper filling pattern to avoid the entrapment of gas while maintaining productivity.

One of the major efforts in this study is to modify the filling simulation system with the capability to directly predict the occurrence of gas porosity developed earlier to interactively determine the proper gate velocity for each and every part of the casting. The pressure required to fill the die cavity can then be obtained from the simulations.

The operation principles and the interactive analysis system developed are then tested on an automotive wheel made by the low pressure casting process to demonstrate how the system can aid in determining the proper pressure–time relations, the $p$–$t$ curve, required to produce a sound casting without sacrificing productivity. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Low pressure casting; Mold filling analysis; Pressure–time relation

1. Introduction

A low pressure die casting machine usually includes a pressurized crucible located below the die table with a feeding tube running from the crucible to the bottom of the die. A schematic diagram of a typical low-pressure casting is shown in Fig. 1. The process is an application of the Pascal’s theory. Where dry gas is used to pressurize the surface of the molten metal in the crucible with relatively low-pressure to overcome the difference between the die and the surface of the molten metal in the crucible and force the molten metal to rise through the riser tube, feeder and gating system, and subsequently to feed the die cavity. When the die cavity is filled, the exerting pressure is increased to pressurize the casting to improve the feeding of shrinkage during solidification. When the casting is completely solidified, the external pressure is released and the molten metal not yet solidified in the feeder and the riser tube flows back to the crucible by the action of gravity.

Producing aluminum alloy castings with a low pressure casting process has the advantage of being semi-automatic and thus saving labor cost as well as obtaining better casting quality and higher yield [1,2]. It is believed that the cost of low-pressure casting is lower than that of die-casting and that the process provides better quality than gravity casting. In spite of the many advantages, the low pressure casting process has not yet been fully appreciated and used widely as it should. The main problem is the lack of understanding of the process. The die design and operation have not been properly incorporated with the machine to make the best of the process [2,3].

A crucial part of the low pressure casting operation is the control of the exerting pressure in the crucible to ensure an even, non-turbulent flow of molten metal through the riser tube and into the die. If the filling is not appropriate, the casting will suffer from filling-related defects such as gas porosity. The current practices rely on the experience of casting engineers and the painstaking step of trial-and-error.
This not only increases the cost but also decreases the quality and yield. As the pneumatic control system of the casting machine becomes increasingly sophisticated, it gives the engineer more freedom to impose necessary change of the exerting pressure. However, this can only be beneficial if the engineer knows how to control the pressure change as each individual casting is being considered. It becomes even more difficult to set the pressure–time relation, the $p-t$ curve, during filling when the shape of the casting is complicated.

Searching the literature, very few studies can be found concerning the operation of the low pressure casting process. The study of the setting of the $p-t$ curve during filling is even more scarce. Basically, the pressure required to fill a casting in the low pressure casting process can be separated in two stages. The first stage is to exert pressure to force the molten metal to rise in the riser tube in a non-turbulent way up to the gate of the casting die, which varies from casting to casting due to the drop of the level of molten metal in the crucible. The second stage is to add additional pressure to push the molten metal to enter the die cavity and fill the cavity in a way that will not cause much turbulence and have the proper filling pattern to avoid the entrapment of gas while maintaining productivity. The pressure required in the first stage can be determined by applying Pascal’s principle and certain industrial experience. The pressure required in the second stage is rather complicated since the shape of the casting is usually complex and the desired filling patterns actually depend on the shape of the individual casting.

The filling of a casting cavity for various casting processes has been studied quite intensively [4–9]. A computer simulation system for the filling of castings with the capability of directly predicting the occurrence of filling-related defects had been previously developed by the authors [4]. It is then the purposes of this study to first determine the pressure–time required to fill the riser tube as quickly as possible without causing disturbance. Then for the filling of the casting cavity, the task is to set up the operation principles that can assure proper filling in the low pressure casting process to obtain the desired properties of the casting. Other than that, the earlier version of the die filling analysis system is modified to be capable of interactively determining the proper gate velocity for each and every part of the casting during filling as the casting is divided, based on its geometric characteristics. While the filling pattern and the velocity profile are calculated by numerically solving the fluid flow equations, the pressure required at the gate can also be computed. Ultimately, an optimal pressure–time relation, $p-t$ curve, for the filling of any particular casting under consideration can be obtained.

2. Theory and methods

2.1. Principles of determining the required pressure

Basically, filling a casting in the low pressure casting process can be separated in two stages. The first stage is to exert pressure on the surface of the melt pool in the crucible to force the molten metal to rise in the riser tube. The pressure required is relatively easy to calculate by applying Pascal’s principle: $p = \rho g H$, where $\rho$ is the density of the molten metal and $H$ is the height difference between the surface of the melt pool and the top of the riser tube. $H$ is a variable, since the level of the melt pool in the crucible keeps dropping as the casting proceeds. One question that needs to be addressed here is how fast the molten metal is to be forced to flow in the riser tube. The principle adopted in this study is that it should be as quick as possible without causing disturbance.

It is known that the fluid flow can be considered as laminar in a tube when the Reynolds number, $Re$, is less than 2100 [9].

$$Re = \frac{DV}{\rho \eta}$$  \hspace{1cm} (1)

where $D$ is the diameter of the riser tube, (cm), $V$ the velocity of the molten metal in the riser tube, (cm/s), $\eta$ is the viscosity of the molten metal, (g/cm-s).

However, the filling of the riser tube does not have to be so conservative. First of all, the flow of molten metal in the tube needs to be non-turbulent, but not necessarily laminar, to avoid entrapping air. Secondly, the criterion for laminar flow to be 2100 is for the fluid to flow in a pipe in a horizontal fashion. In the low pressure casting process, the molten metal fills the riser tube in a vertical way and from the bottom. From industrial experience, it is known to be
optimal to fill a riser tube of 50 cm length and 9 cm diameter in approximately 5 s [10]; this is a rising velocity of 10 cm/s. With the properties of the molten aluminum, the Reynolds number can be as high as 21 000.

The second stage is to keep adding pressure to push the molten metal from the gate to fill the cavity. The conventional principle is to have the molten metal flows as slowly as possible on the basis of reducing turbulence. This has the disadvantages of low productivity and possible premature freezing, which results in failure of the casting. It is also not necessarily true that slow filling is always beneficial to the quality of the casting as far as gas entrapment is concerned. The principle adapted in this study is that, depending on the geometry of the casting, a favorable flow pattern should be determined by the engineer. In order to do this, the engineer can first divide the casting into several parts depending on its geometric characteristics and the various mechanical properties required of the different parts of the casting. Then the engineer can decide which part should be filled first, which part is next, and so forth. The engineer can also determine how quickly or how slowly each individual part should be filled. Then the engineer chooses a gate velocity. Through the aid of a die filling simulation system, the engineer is able to decide whether the chosen gate velocity can result in a desirable flow pattern. If not, the gate velocity is modified and the flow pattern is simulated again until a desirable flow pattern is obtained for that particular part of the casting. The process is repeated until the whole casting is filled.

It is then obvious that the die filling simulation program needs to be interactive. It is also necessary that the simulation program can directly depict the extent of gas entrapment in the casing part that is being filled. The flow information obtained from a conventional die filling simulation program are velocity profiles and flow patterns, which are difficult to relate to gas defects, especially when a three-dimensional casting of complex shape is being considered. The engineer can examine the filling pattern under the given gate velocity to see if it is desirable or not. If not, a new gate velocity can then be set and the calculations resumed. The process iterates until the whole casting is filled. Then an ideal relation for gate velocity versus time can be obtained during the filling of the low-pressure casting. While calculating the filling pattern and the velocity profile, the required pressure at the gate can also be computed. With the combination of the two stages during the filling of the casting, the relation between pressure and time, the $p-t$ curve, can be obtained.

2.2. Mathematical model for die filling simulation

2.2.1. Computational fluid dynamics technique

The flow of molten metal during die filling is highly transient; the amount and location of the melt changes. Calculation of the location of the molten metal must be an integral part of the computational techniques used to model it. A family of computational techniques call MAC [11], SMAC [12], and SOLA-VOF [13] are well suited for handling these problems. Although they differ from each other in the way that they keep track of the free surface location and satisfy free surface boundary conditions, they are based on the same principles. The technique used in this study, named SOLA-MAC [1], is basically a combination of the appropriate features of the individual techniques mentioned above, which are needed for application in the low pressure casting process.

2.2.2. Technique highlight

The technique uses a finite difference scheme for the mathematical analysis of the fluid flow problems. Like most numerical techniques, it first divides the system; i.e. the configuration of the die cavity under consideration, into a number of subdivisions called cells. Then a set of imaginary markers is introduced into the system to represent the location of the fluid at any instant. In the technique, the cells are designated as full, surface, or empty, based on the locations of the fluid markers. A full cell is one that contains at least one fluid marker and all of its neighboring cells contain fluid markers also. A surface cell contains at least one marker but has at least one neighbor without a fluid marker. An empty cell is any cell with no fluid markers. Collectively, the full cells constitute the interior region and the surface cells constitute the surface region. The velocity field of the moving fluid domain (interior region plus surface region) can be calculated by the application of fluid dynamics principles. Next, the fluid markers are moved according to the calculated velocity field in order to represent the new location of the fluid domain.

To predict gas entrapment and the related defects during the filling stage of the low pressure casting process, a tracing technique called ‘air marker method’ [4] is used in this study to work along with the die filling technique. In this method, another set of markers is used other than the one for molten metal to represent the gases in the die. When the simulation starts, a set of markers is evenly distributed in the die to represent the existence of the gases. The air markers are moved with velocities that are weighted averages of the nearest cell velocities like the fluid markers. In other words, air markers will not move before their neighboring cells become full/surface cells. As the neighboring cells become full/surface cells, the fluid markers and air markers are moved according to their velocities and form a new distribution of the fluid and air markers. In this way, air markers are pushed by the movement of the flowing melt, as shown in Fig. 2. By observing where the air markers exist at the end of filling, it is rather easy to observe where air entrapment will occur and how serious it will be.

2.2.3. Calculation of velocity and pressure fields in the moving melt

After the flow domain and the corresponding interior and surface regions of the domain have been identified,
the velocity and pressure fields within the flow domain are calculated. The physical principles that govern the flow behavior in the interior region are different from those in the surface regions.

In the interior region, the fluid dynamics principles to be obeyed contain the continuity equation and momentum equation. In the Cartesian coordinate system, these equations can be described as follows.

1. Continuity equation

\[ D = \frac{\partial U_i}{\partial x_i} = 0 \]  \hspace{1cm} (2)

where \( D \) is divergence, and \( U_i \) is the velocity components in the \( x_i \) direction, (cm/s).

2. Momentum equation (Navier–Stokes Equation)

\[ \frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right) + g_i \]  \hspace{1cm} (3)

where \( t \) is time, (s), \( P \) the pressure, (g/cm \(^2\)), \( \rho \) the density of the melt, (g/cm \(^3\)), \( g_i \) the component of gravitational constant in the \( x_i \) direction, (cm/s\(^2\)) and \( \nu \) is the kinematics viscosity, (cm\(^2\)/s).

When solving these equations for \( U_i \) and \( P \), a SOLA scheme is used. This derives a pressure adjustment term from Eqs. (2) and (3) as follows:

\[ \Delta P_{i,j,k} = -D_{i,j,k}(\partial D/\partial P) \]  \hspace{1cm} (4)

where:

\[ \frac{\partial D}{\partial P} = \frac{1}{\rho} \left( \frac{1}{\Delta x_i(\Delta x_i + \Delta x_{i+1})/2} + \frac{1}{\Delta x_{i+1}(\Delta x_i + \Delta x_{i+1})/2} \right) \]

\[ + \frac{1}{\Delta y_j(\Delta y_j + \Delta y_{j+1})/2} + \frac{1}{\Delta y_{j+1}(\Delta y_j + \Delta y_{j+1})/2} \]

\[ + \frac{1}{\Delta z_k(\Delta z_k + \Delta z_{k+1})/2} + \frac{1}{\Delta z_{k+1}(\Delta z_k + \Delta z_{k+1})/2} \]  \hspace{1cm} (5)

in which \( \Delta x_i, \Delta y_j, \Delta z_k, \Delta x_{i+1}, \Delta y_{j+1}, \Delta z_{k+1} \) are the space increments of the \( i \)-th, \( i+1 \)-th, \( j \)-th, \( j+1 \)-th, \( k \)-th and \( k+1 \)-th cell in the \( x \), \( y \) and \( z \)-axis, (cm), and \( \Delta t \) is the time interval for computation (s).

Initially, a tentative velocity field is calculated from the Navier–Stokes equations with a prescribed or assumed pressure field. While not satisfying the zero divergence requirement; \( D \neq 0 \), a pressure adjustment term; \( \Delta P \), is calculated based on Eqs. (4) and (5) and the amount of divergence. The pressure adjustment terms are then used to adjust the tentative velocity field. The process is iterated until zero divergence is satisfied for all the cells in the interior region. The advantage of this algorithm is that pressure and velocity are both included in the iteration and thus converge is achieved faster. Extra caution should be exercised for the calculation of pressure here, since it affects the accuracy of the velocity calculation and the pressure itself is the most important quantity to be obtained in this study. It should also be noted that the pressure value calculated here should be divided by the gravitational acceleration to obtain the actual pressure required.

In the surface region, the continuity equation, however, does not hold in the state of zero divergence because the flow domain may be expanding or shrinking in the surface region. Instead, the following conditions should be satisfied on the free boundaries: (a) stress tangential to the surface must vanish; and (b) stress normal to the surface must balance the externally applied normal stress.

Accurate application of the free surface boundary conditions requires accurate knowledge of the free surface orientation, which is difficult to obtain. Without resolving the surface orientation, the technique proposes some simplifications to the treatment of the free surface boundary conditions. The details can be found in Ref. [12].

3. Test results and discussion

To demonstrate how the developed system can aid the engineer to determine the optimal pressure–time relation; the \( p–t \) curve, an aluminum casting of an automotive wheel produced by the low pressure casting process is employed in this study. A photograph of the aluminum wheel is shown in Fig. 3. The wheel is of 37.04 cm diameter and 17.91 cm height. The low pressure casting machine with the crucible and the riser tube in this study is shown in Fig. 4. The
crucible is of 70 cm diameter and the molten aluminum is initially filled to 47.35 cm. The riser tube is of 87.35 cm length and 19 cm diameter. The height difference between the top of the riser tube and the molten aluminum level in the crucible is 50 cm. The gate to the cavity in the die is round, with a diameter of 5 cm.

3.1. Determination of the $p$–$t$ curve for the filling of the riser tube

As discussed in Section 2.1, the pressure required to fill the riser tube for the first casting can be calculated by applying Pascal’s principle. With the density of the molten aluminum taken as 2.385 g/cm$^3$ and the dimensions of the crucible and the riser tube as shown in Fig. 4, the required pressure is 0.1193 kg/cm$^2$. To fill the riser tube as quickly as possible without causing turbulence, the velocity of the molten aluminum can be easily calculated as 10 cm/s based on Eq. (1) and the Reynolds number of 21 000. With this velocity, the time required to fill the riser tube is 5 s. This means that the pressure required to fill the riser tube in the first stage of the casting is from 0 to 0.1193 kg/cm$^2$ within 5 s, as shown in Fig. 5. For the second casting, the melt pool level is dropped by the amount of 1.115 cm, which can be calculated by the volume of the casting, which is 4118.4185 cm$^3$ for the wheel casting, and the cross-sectional area of the crucible. Then the pressure required should take this amount into consideration, which is not a difficult job in the computer program.

3.2. Determination of the $p$–$t$ curve for the filling of the die cavity

Judging from the shape of the aluminum wheel and its placement in the die, it is quite natural to divide the casting into three parts as shown in Fig. 3. The first part is the central hub, which connects to the transmission device of an automotive with screw bolts. The second part is the rim; or the wheel flange. The third part is the spokes, which connect the central hub and the rim. The spokes are the mechanically crucial area of the wheel, as the maximum load exists in these spokes when the wheel is in service.

The next step is to determine the gate velocity distribution in order to obtain a favorable flow pattern to fill the casting. In order to do this, it is necessary to have certain insights to the filling patterns in the cavity under different gate velocities. From industrial experience [10], it is known that the gate velocity to fill the casting cavity should be in the range of 10–30 cm/s. Therefore, the filling patterns under constant gate velocities of 10, 15, 20, 25, and 30 cm/s are investigated. Before the analysis, the casting is divided into 65 910
elements (65 × 39 × 26). The mesh system for half the casting is shown in Fig. 6 (the number of the following figures should be changed accordingly). Typical results of the distributions of velocity and air entrapment during the filling of the wheel casting cavity for the various gate velocities are shown in Figs. 7–11. Since the 3-D results are very difficult to visualize, only 2-D results of critical sections are shown. For the lowest gate velocity of 10 cm/s, trapped air particles

Fig. 6. The mesh system of the automotive wheel casting.

Fig. 7. Velocity profiles and air entrapment conditions as the casting is filled with constant gate velocity of 10 cm/s.
Fig. 8. Velocity profiles and air entrapment conditions as the casting is filled with constant gate velocity of 15 cm/s.

Fig. 9. Velocity profiles and air entrapment conditions as the casting is filled with constant gate velocity of 20 cm/s.

can be found in the spokes and the rim, as shown in Fig. 7. The air particles in the rim are relatively sparse and may not present a critical problem for the wheel. However, the air particles in the spokes, which are found to have been trapped earlier in the central hub and later traveled to the spoke, can be a serious problem for the wheel casting. For the gate velocity of 15 cm/s, similar results are obtained. For the gate velocity of 20 cm/s, Fig. 9 shows that a certain
number of air particles are concentrated in the rim while the rest of the casting is relatively clean. For the gate velocity of 25 cm/s, concentrated air particles are found in the rim near to the outer circumference and near to the spokes, as shown in Fig. 10. For the highest velocity of 30 cm/s, flow turbulence is found to exist in the central hub and the intersections of the rim and the spokes.

From the above observations, it is proposed in this study...
that to properly fill the wheel casting, the central hub should be filled with a gate velocity somewhere between 20 and 25 cm/s and the spokes should be filled slowly. When the spokes are filled, the rim part can be filled as quickly as possible. Based on this idea, an interactive procedure to determine the proper gate velocity to fill the wheel casting is demonstrated as follows.

First, the gate velocity is set at the highest of 30 cm/s, and
Fig. 14. Velocity profiles and air entrapment conditions as the spokes is filled with a gate velocity of 25 cm/s.

numerical simulations are conducted to show how the molten metal flows into the cavity and fills the central hub. It can be seen from Fig. 12 that molten metal starts to flow into the spokes, area before the central hub is completely filled. This means that for this casting, it is not practical to expect to completely fill the central hub first and then to fill the spokes. It is therefore decided that the first stage during filling should be ended when the spokes are filled. When the result as shown in Fig. 12 are examined, if found that turbulence exists and a significant number of air particles are found in the bottom areas of the hub, which is considered as an undesired situation. Then the gate velocity

Fig. 15. Velocity profiles and air entrapment conditions as the spokes is filled with a gate velocity of 15 cm/s.
is reduced to 25 cm/s. When the first step of the filling is completed, the flow conditions are again examined and it is found that significant improvement has been achieved, as can be seen in Fig. 13. Therefore, the gate velocity of 25 cm/s is accepted as the proper inflow velocity for the first step.

Numerical simulations are then continued after the first step with the gate velocity of 25 cm/s until the spokes and the bottom part of the rim have been filled. The results of the flow patterns and air-particle distribution at the end of the second step are shown in Fig. 14. As the figure shows, a

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**Fig. 16.** Velocity profiles and air entrainment conditions as the spokes is filled with a gate velocity of 10 cm/s.

**Fig. 17.** Velocity profiles and air entrainment conditions as the hub top and rim bottom half are filled with a gate velocity of 25 cm/s.
large number of air particles exist in the spokes and the bottom part of the rim, which is clearly not acceptable. Then the gate velocity for the second step is reduced to 15 cm/s. The results are shown in Fig. 15. As the figure shows, the extent of air entrapment is still quite severe. The gate velocity is further reduced to 10 cm/s. As can be seen from Fig. 16, most of the air particles are pushed out of the spoke region but a certain number of air particles still exist in the rim. However, the particle distribution in the rim is relatively sparse, which is considered as acceptable. Therefore, the gate velocity for the second step is set at 10 cm/s.

Fig. 18. Velocity profiles and air entrapment conditions as the hub top and rim bottom half are filled with a gate velocity of 20 cm/s.

Fig. 19. Velocity profiles and air entrapment conditions as the hub top and rim bottom half are filled with a gate velocity of 15 cm/s.
When the bottom of the rim is filled, the filling of the casting is considered to enter the third stage, which is mostly to fill the top portion of the central hub and the bottom half of the rim, where an expansion in the rim diameter exists.

The gate velocity is first set at 25 cm/s based on the idea of quick filling of the casting. The results of the filling patterns and the distribution of air particles are shown in Fig. 17. It can be seen that a large number of
air particles again appear in the bottom part of the rim. Then the gate velocity for the third step is reduced to 20 cm/s. Fig. 18 shows that similar problems still exist. The gate velocity is further reduced to 15 cm/s. The filling conditions as shown in Fig. 19 are found to be smoother and the air particles concentrate in the top portion of the rim near the flow front, which is more acceptable since the air particles still have chance to be

Fig. 22. The $p$–$t$ curve for the wheel casting when the gate velocity is set at 25, 10, 15, 25 cm/s.

Fig. 23. The $p$–$t$ curve for the wheel casting when the gate velocity is set at a constant velocity of 20 cm/s.
eliminated from the casting. Therefore, the gate velocity for the third step is set at 15 cm/s.

The last step is to fill the top portion of the rim. It is anticipated that fast filling should not create any problem in the casting. The gate velocity is then set at 20 cm/s. The results as shown in Fig. 20 confirms the above anticipation. The gate velocity is further increased to 25 cm/s to further shorten the filling time. The results as shown in Fig. 21 again show that satisfactory filling condition can be obtained. Therefore, the gate velocity for the last step is set at 25 cm/s.

From the above description, the wheel casting considered here can be properly filled in four steps. The gate velocities for these four steps are set at 25, 10, 15, 25 cm/s, respectively. As the gate velocity distribution is determined and the numerical simulations are conducted for the whole filling stage, not only can the filling patterns and velocity profiles be calculated but the pressure required at the gate can be obtained. With the incorporation of the pressure–time relation required to fill the riser tube calculated in Section 3.1, the whole pressure–time relation; the $p-t$ curve, can be obtained for the filling of the casting as shown in Fig. 22. When multi-step filling is compared to one-step filling with constant gate velocity, the case of a constant gate velocity of 20 cm/s is chosen, since it has a similar filling time as the multi-step filling. The $p-t$ curve for the constant velocity of 20 cm/s is shown in Fig. 23. When the two figures are compared, significant difference can be realized.

4. Conclusions

In this work a filling simulation system with the capability to directly predict the occurrence of gas porosity previously developed by the authors is modified to interactively determine the proper gate velocity for each and every part of the casting. The pressure required to fill the die cavity is obtained from the simulations.

The operation principles and the interactive analysis system developed were tested on an automotive wheel made by the low pressure casting process and it was demonstrated how the system can aid in determining the proper pressure–time relation required to produce a sound casting without sacrificing productivity.

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