A development of virtual prototyping manufacturing system for high pressure die casting processes

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Abstract

High pressure die casting (HPDC) magnesium components are increasingly used worldwide in these few years because of the excellent properties that magnesium alloys can offer meet the new product requirements. With the increasing worldwide application for the use of magnesium parts, there are many research and development projects targeted at advancing the technologies of HPDC have been carried out. However, the real optimized mold design and production of defect free castings remains a challenge for die casters. For many HPDC magnesium products, especially the case with porosity-free and highly cosmetic requirement, the challenge not only comes form lacking of detail understanding of how molten magnesium alloys fill mold cavity and form defects but also from improper preliminary part design. A virtual prototyping system integrating several software and hardware that can be served as an effective tool for both part and mold design engineer in evaluating the part manufacturability is proposed in this study. Also, the major cause of defects that is the predominant cause of rejection for thin walled, highly cosmetic requirement and leaking-free magnesium parts are investigated in this study.

1 Introduction

Although numerical simulation tools allow casting engineers to gain insight into many aspect of the casting process, in real application, simulating fluid flow is the most computationally intensive part of the HPDC modeling process. Even after reviewing the simulation results, engineers often still cannot learn from the simulation quantitatively and optimize the whole process. The problem is, what design features and process variables are important and should be modified in preventing the occurrence of defects. Therefore, it is necessary to establish a systematic approach to make quantitative prediction of casting defects efficiently. Only when defects can be quantitatively measured and identified in simulation efficiently, optimization of mold design and process variables can be achieved early at the design stage. To quantitatively measure the defects, a series of direct experimental and numerical investigation were conducted in this study. Also, the process variables in the magnesium die casting are analyzed to detect significant correlations with the occurrence of defects in numerical simulation.

2 Virtual prototyping manufacturing system for HPDC part

Generally speaking, manufacturability or so called as castability of a HPDC part is determined by three major factors: product specification, mold design, and machine setting as shown in Figure 1. Conventional HPDC parts development adopts an "over the wall" sequential process. Most of the HPDC part designer consider only the functional requirements and pass the manufacturing issues to the die casting engineers. Most of the time, product design forwarded to the die caster is too late for significantly alter in part features for manufacturability. The major reason is the lack of effective system that can support for the incompatibilities between design and the manufacturing process. Once the mold was made, changes make to the mold are expensive. It is not only because that most of the mold design processes are irreversible, but also mold modifications risk the possibility of creating other unexpected problems. It is very common for die casting engineer to find out even after many mold changes, they still cannot really optimize some castings. The objective of this study is to develop a systematic method and environments that can supports design decision-making and simulate manufacture process concurrently. Therefore, appropriate part modification that compromise between design and manufacture can be achieved and resolve problems before they become irreversible. In this approach, manufacturability can be greatly improved as shown in Figure 2. Taking advantage of the advancement of the accuracy and efficiency of design and simulation tools, synergy and time efficiency can be really achieved.

The proposed virtual prototyping manufacturing system consists of a product information management (PIM) system, CAD tools, flow simulation tools, and manufacturing variables feedback system for verification. The environment is flexible so that engineering tools can be incorporate or substitute with least efforts depend on the product requirements.

A customized GUI program was developed to be served as a query interface and speed up the design iteration process. Most of the software and hardware tools except PIM used in the system are commercially available for specific design simulation and verification works. This integrated environment provides die casting engineer an environment for efficient mold design and analysis.

2.1 Product Information Management (PIM)

After verifying with the product design engineer for detail specifications, die caster engineer usually decide runner and gating system by experience and data of previous similar parts. A graphic user interface PIM software was developed base on empirical gating design. With more detail knowledge of the design gained form simulations, better design decisions can be made. The advancement of web base communication tools combined with 3D CAD system and spreadsheet functions that

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can be used to organize the experience and specification data to support decision-making in discrete form in order to evaluate an initial concept design. The PIM system integrated with a CAD tool will directly generate information of the solid model and design intension that serves directly the down stream design and manufacturing simulations.

2.2 Parameterized runner and gating CAD software

The part features, runner and gates affect how the metal fills the cavity. Since the geometry of the part can be considered as a design constraint. Filling pattern is directly related to the geometry of runner and gating position. There is specialized runner and gating CAD software allowing the mold design engineer to parameterize the runner and gating geometry with less effort. By changing the geometric parameters, mold design engineer can evaluate the relation to varying filling times, gate speed, flow direction near the gates and PQ^2 operating windows. The flow vector diagram provided by the software can be use to evaluate the flow direction near the gates. This feature is especially useful in design the runner and gating system form scratch. Since simulating fluid flow is computationally expensive. This feature can be served as an efficient tool to increase the accuracy of "initial guess" toward the optimized runner and gating design. Parameterized runner and gating software can be utilized as a standardized design tool that can greatly increase the design iteration efficiency. On the other hand, there are several disadvantages in using this kind of runner design software:

First, the flow vector diagram may mislead mold design engineer that metal flow during filling process will be as continuous and uniform as shown in the diagram. In actual application, it was found that non-uniform gate velocity and geometry discontinuity will cause the separation of flow free surface in forms of droplets and swirling which are extremely unfavorable flow patterns for magnesium parts than other alloy HPDC parts.

Second, The flow angles provided in the diagram is correct only at some specific gate velocity. One should keep in mind that the gate velocity is time dependent variable that depends on the performance and setting of HPDC machine. The flow angle is also time dependent variables. The influence of flow angle variation during the filling is difficult to evaluate.

Third, the provided runner geometric parameters may not be necessary complete for

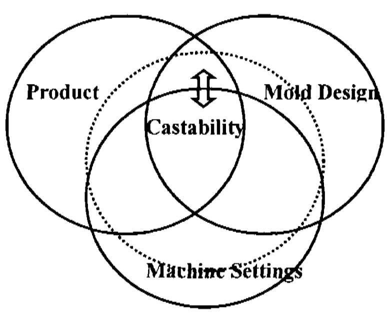

Figure 1: Castibility for sequential development process

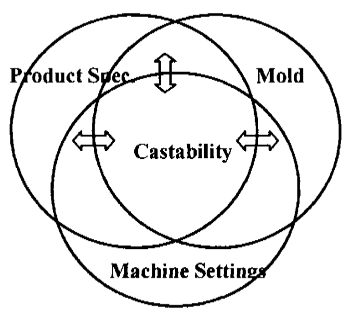

Figure 2: Castibility for concurrent design and manufacture

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constructing a real optimization runner. That is, the geometric parameters provided by the software sometime may constrain the concept of runner and gating system design [5].

The most important factors governing the occurrence of cold flow marks, blisters and cracks are: wall thickness, filling pattern and die temperature. The combination of these factors determinate the conditions that metal confluence will completely fuse or not during solidification. Therefore, the filling time base theory and flow vector diagrams make sense only under the condition when the flow is continuous. If flow breakup occurs, there are some specific regions of cavity sometime fills and then empties again. The use of global filling time theory is not proper for these specific regions of cavity.

2.3 Flow simulation software

Due to lack of simulation tools, die casting engineer had to rely on experience and guess work to design the mold before the first shot. Even after the first shot, engineers gained limited information by examining the test part. Physical experiments, such as "short shots" adopted by die casting engineers; do not provide enough information to solve the defect problems most of the time, especially for the confluence of weld in the cavity, since after the injection system is stopped, the liquid metal will continue to flow in the partially filled cavity before solidification. This flow condition is quite different from actual conditions in production. To improve understanding to the filling model, there are many CFD software developed for implementing HPDC simulation. However, to simulate the complicate physical HPDC process within reasonable amount of time is not an easy task. Major obstacles include time-consuming in constructing and solving the numerical model. The complexity of the numerical scheme solving strategy may vary form filling or solidification only model to a complicate model that coupling filling, solidification, and heat transfer at the same time. It is reasonable to study filling flows separately from solidification in real application [1]. The fact that the solidification time is much longer than the filling time implies that, during the filling period, the solidification portion of the metal is so small that it has little effect on the flow of liquid metal for most of the magnesium HPDC parts. Some experiments show that the maximum flow length of typical magnesium alloys AM20, AM50, AZ91 may vary form 350 to 500 mm at the gate speed of 80m/sec with part thickness of 1.4 mm [2]. The increasing of solidification pressure and gate velocity had no significant on the temperature distribution in the die with flow length about 300 mm [3]. Therefore, before quantitative decisions for numerical model can be made, variable sensitivity involved in the simulation should be evaluated depends on the product specification and geometry. A common alternative for magnesium HPDC simulation is the assumption of using a filling only and solidification only model for initial simulation. For example, it is reasonable to use filling only model for magnesium HPDC flow analysis for parts with flow length less than 300mm with critical part thickness 1.4 mm. The use of this solving strategy will reduce the governing equations describing metal flow and greatly simplify the computational effort in numerical modeling. This means, less computational time will be needed to obtain the filling information in magnesium HPDC.

Compared with other factors and process variables, flow behaviors that tend to entrap gases and oxide inclusion will dominate the occurrence of defects. The most prevalent defects for magnesium HPDC parts are strongly related to the occurrence of swirling and splashing filling pattern that is cause by excessive liquid breakup most of the time. An idea runner and gating system should produce a continuous filling pattern with uniform velocity. With systematic tool integration, metal flow could be guided to the critical regions with priority if uniform filling condition is impossible due to the discontinuity in cavity geometry.

2.4 Manufacture parameters feedback tools

Even with the use flow simulation tools, there do always exist discrepancy between prediction and simulation. Since simplified numerical model is used and also there is no way to measure some actual manufacturing parameters such as injection shot trace, actual mold temperature etc before the first shot. If further refinements are needed for the mold design or process parameters, the assumed parameters in the prediction should be replaced with measured value. Therefore, critical manufacturing parameter feedback tools are need for process refinements. For typical die casting machine, the plunger speed is programmed by specifying the plunger velocity as a function of plunger position on the shot sleeve. Although this kind of program setting is very suitable for machine operation since the transition slow to fast shot phases can be calculated in term of casting volume. It is not suitable for boundary conditions input for flow simulation that use plunger velocity shot trace as a function of time for its boundary condition input. It is necessary to install devices that can control or at least collect the plunger shot trace as a function of time if the function is not provided by the die casting machine. It should be aware that most of the time the actual shot trace in operation could be different from the original setting. If the die casting machine export injection shot trace with low resolution that could not reveal the fluctuation that may influence the filling behavior, one should consider install more sensitive sensors for more accurate shot trace control and collection devices.

2.5 Tool integration

The proposed tool integration is desirable to create a virtual environment for magnesium HPDC development. With such tool integration, a systematic design, including parametric study for the mold design and trade-off study for detail manufacturing parameters, can be conducted to improve the efficiency with a minimum number of mold design iteration. The simulation technology potentially minimizes the needs for hardware tests. With the improvement of substantial modeling and simulation performed, improper design defect encountered during the hardware test will not be common, thus, shorten the feedback loop for process modifications.

3 Experiments and examples for HPDC parts

The proposed system has been applied for real applications. Selected experiments and applications are described in this section. First two cases were tested on FRECH hot chamber machine with 315kN locking force. The third example was tested on both FRECH hot chamber machine with 500kN locking force and BULER cold chamber machine with 530kN locking force for direct comparison.

3.1 Example 1: Flat plate for experiment:

A magnesium (AZ91D, AM60) flat plate with dimension 140x100x1mm is designed for this study (Fig. 4). The surface of the specimen is flat and smooth; therefore, cosmetic defects can be detected easily. With the same gating area and location, a gating system constant cross-sectional area in the runner is design as shown Figure 1. After injection, it is found that the cosmetic quality of the experiment plate is poor. Even in the gated zone, tiny cracks appear randomly on the surface. This can be verified form simulation (Fig. 5). The gating system tends to produce flow pattern with excessive liquid breakup and swirling. After geometric changes are made to the gating system, under the same injection parameters, more continuous and uniform flow pattern is produced and verified by simulation (Fig. 6). Although using the same gating area and location, most of the cosmetic defects do not occur in the modified model.

3.2 Example 2: Thin-walled casing with highly cosmetic requirements

Using the same approach, modifications are made to an existing case with problem of cosmetic defects. Although all injection parameters have been adjusted, the improvement is quite limited. With the use of the proposed system, the occurrence of cosmetic defects predicted by simulation (Figure 7) are consistent with existing part as shown in figure 9 and figure 10. After minor modification in the existing gating system and part features, continuous and uniform flow pattern can be produced as shown in figure 8. The modified model does greatly reduce the occurrence of the surface defects.

3.3 Example 3: Gearbox with cosmetic and porosity-free requirements

A gearbox component with average thickness of 4 mm that is relatively thick part compared with previous examples is investigated in this study. Both hot chamber and cold chamber machine are use for direct comparison. The component requirements are both cosmetic and leaking-free on the critical regions near the hubs. Gating system is designed to produce desired flow pattern.

The controlled metal guided to the hubs, as shown in figure 13, can greatly reduce the possibility of air bubbles becoming entrapped within the critical regions. Also, venting and overflows can be placed at proper positions and proper pressure within the casting can be maintained without guessing works. Common casting defects for this kind of component are porosity, cracks and blister. There are different mechanisms involved in porosity formation cavity. In most conditions, the entrapment of air is formed in the cavity, there is a chance that the air entrapment is formed in the horizontal shot sleeve for a cold chamber machine. Blister defect differs from the common defect of shrinkage porosity in that the cavities are a result of relatively high pressure in unsolidified regions rather than low pressure With the introducing of accurate shot trace control and feedback devices, engineers can not only avoid air entrapment in the shot sleeve by using simulation tool (figure 16) but also really measure the performance of the ejection systems (figure 15). With the use of the integration system, the quality and yield rate for this component are very high (figure 14).

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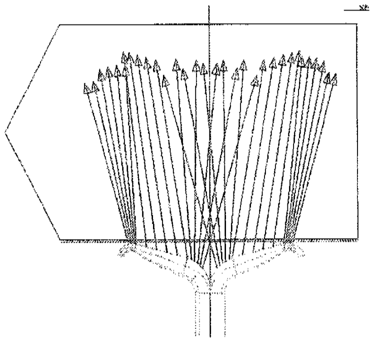

Figure 3: Parameterized CAD software for gating system

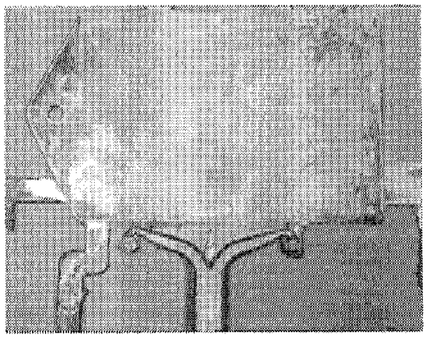

Figure 4: Actual flat plate casting

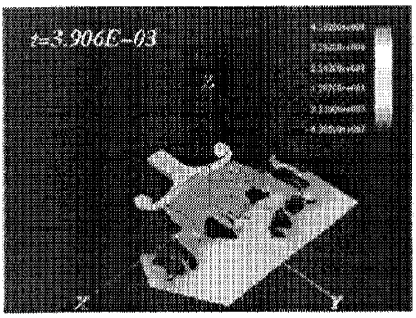

Figure 5: Flow simulation for original gating System

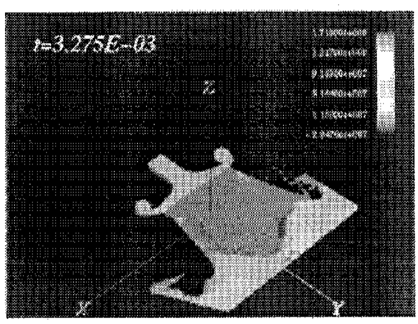

Figure 6: Flow simulation for improved gating system

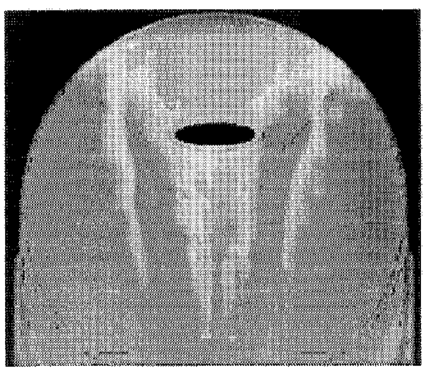

Figure 7: Flow with excessive liquid breakup

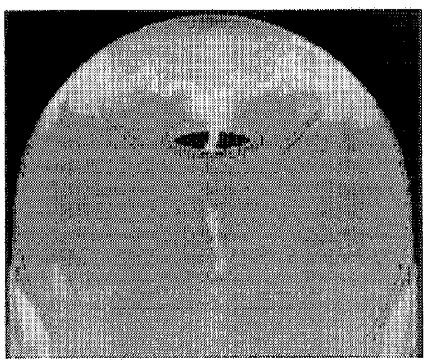

Figure 8: Flow with improved flow pattern

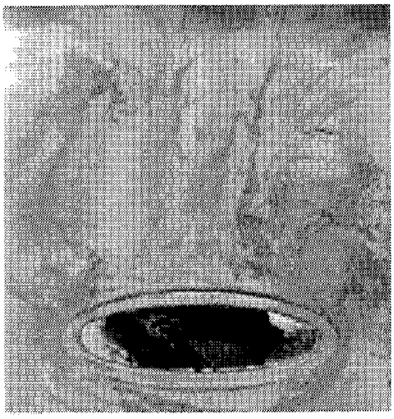

Figure 9: Defect location consistent with simulation

Figure 10: Residual flow drift the defect form predicted location

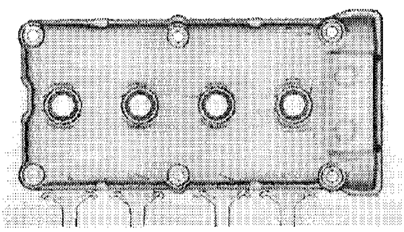

Figure 11: Gearbox gating system design

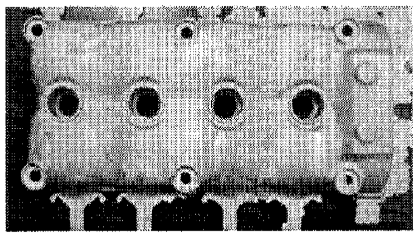

Figure 12: First shot gearbox

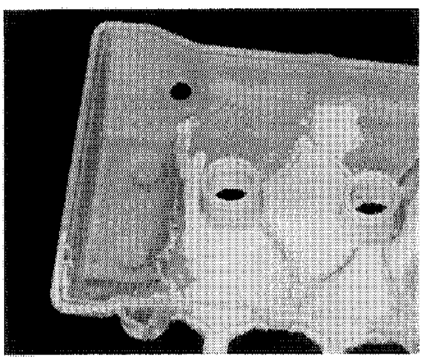

Figure 13: Controlled flow pattern

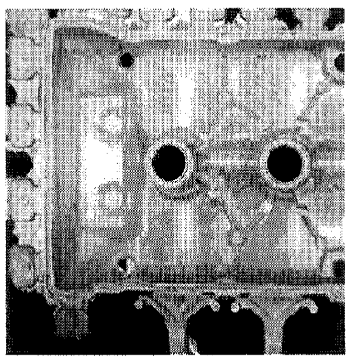

Figure 14: Real casting for gearbox

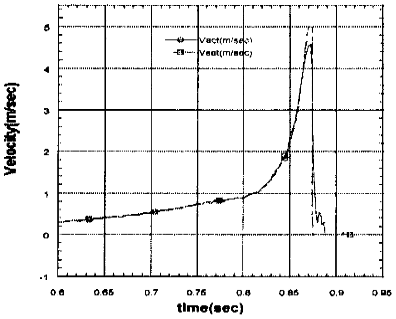

Figure 15: Predicted and measured shot trace on a cold chamber machine

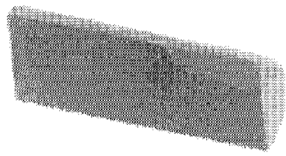

Figure 16: Flow simulation in the shot sleeve

4 Conclusions

In real application, simulation are useful tools to predict the location of air entrapment and the distribution of the inclusion defect in the filling mold, however, one should still be aware of that the trend of filling pattern is stable or not. The instability may be classified into two types. One is caused by unstable filling pattern itself and the other is caused by poor controllability of plunger speed. If the filling pattern is unstable, the numerical model is quite susceptible to any small perturbations. In magnesium HPDC, thinner part and increased gate speed make the prediction even more difficult. Since these perturbations may come form numerical bifurcation itself or small protrusion like ejector pins or roughness on the mold surface. The measurement of actual accurate shot traces is very important for improving the accuracy of the simulation model and verifying the controllability of the machine. It is found that some die casting machines with poor controllability of plunger speed makes it very difficult or even impossible to produce stable and consistent injection shot trace. This is especially obvious for thin parts with relative small cavity volume. The reason is that the use of die casting machine size is determined by projection area of the casting part instead of the volume. That is, the plunger strike distance is proportional to the thickness of the part thickness for the same machine. For ultra-thin casting part such as 0.8 mm in example 2, the plunger strike distance can be less than 8 mm that makes the control of plunger speed during cavity filling stage very difficult if no impossible. In this study, two type of machine are use for comparison. Let along the overall machine performance which is not the scope of this study, it is found that Buler machine has superior controllability of plunger speed.

The most prevalent incidence of magnesium HPDC defects is cold laps in thin part or blisters in thick part. Form this study, It seems the main cause for the occurrence of cold laps and blister is that separate streams accompanied with air entrapment of metal filling fail to fuse before final solidification. If metal surface fold over or collide during the filling process, impurity on the surface or air will then be trapped in the interior of the casting part. Since magnesium alloy is more active than aluminum, for magnesium HPDC the main impurity source comes from oxide formation that is proportional to the surface area and exposure time of the metal flow during cavity filling. Some investigations show that the mold filling ability of magnesium alloy is 20% to 50% lower than that of aluminum alloy [2] [3]. Increasing aluminum content improves the die filling ability [4]. From this study, it seems that under the same filling conditions for magnesium alloys the latent heat of different magnesium alloy may play a crucial factor for mold filling ability. It may be also explained as the ability of molten magnesium alloy at free surfaces to fuse before its final solidification. The main difficulties arise in numerical simulation of HPDC processes is that the physical behavior of detail material properties and boundary conditions are very complex. These do not include gases due to combustion or volatilization of die or plunger lubricants and gas dissolved in the melt. To meet the time efficiency requirement, one should compromise between the accuracy and efficiency. The proposed system is focus on providing optimized and feasible scheme at the design stage instead of focus on predicting the physical phenomenon.

The systematic approaches introduced in the concurrent design and manufacture system does not focus on superseding the generality and accuracy of existing commercial simulation software. The proposed approach specializes in the taking full advantages of integrating existing tools to support all segments of HPDC process.

Acknowledgments

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