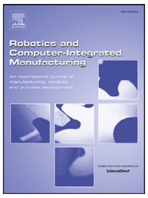
Robotics and Computer–Integrated Manufacturing 55 (2019) 147–153

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim



Computer aided engineering (CAE) simulation for the design optimization of gate system on high pressure die casting (HPDC) process

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ARTICLE INFO

Keywords:
CAE simulation
HPDC
MFA
Gate design
FDM
Flow junction zones

ABSTRACT

A most important progress in civilization was the introduction of mass production. HPDC molds are one of main technologies for mass production. Due to the high velocity of the liquid metal, aluminum die-casting is so complex where flow momentum is critical matter in the mold filling process. Actually in complex parts, it is almost impossible to calculate the exact mold filling performance with using experimental knowledge. Due to this condition in the design procedure, the simulation is becoming more important. Simulation can make a casting system optimal and also elevate the casting quality with less experiment. The most advantage of using simulation programs is the time and cost saving of the casting layout design. The condition selection of HPDC mainly relied on the experience and expertise of an individual worker in casting industries. Systematic knowledge accumulation of die casting process was an essential matter to get optimal process conditions.

In present casting industries, product development paradigm is shifting from traditional trial-and-error to proof-of-concept based on CAE -enabled simulation. Due to the high velocity of the dynamic behavior of the casting system in working conditions, aluminum die casting is a very complex process in which flow momentum is a critical issue in the mold filling process. In the new production development paradigm, CAE simulation plays an important role because it models the entire casting process and reveals the dynamic behavior of the casting system. In this research, CAE simulation was performed by using the simulation software (AnyCasting) in order to optimize the gate and runner design of an automobile part (Oil Pan_BR2E) which is well known and complicated to achieve a good casting layout. Filling analysis was used to find out the size and location of the gate and proper runner system design. By the modification of the gate and runner system and the configuration of overflows, internal porosities caused by air entrapments were predicted and reduced remarkably. With the solidification analysis, internal porosities caused by the solidification shrinkage were also predicted.

1. Introduction

The method of HPDC is one of the most important techniques for manufacturing automobile parts and electronic parts, and one of the economical casting techniques that can manufacture complex shapes at one time. When manufacturing HPDC mold, generally, the casting layout design should be considered based on the relation among injection system, casting condition, gate system, and cooling system. In current casting industries, the design and development of a casting layout is a trial-and-error method based on heuristic know-how. The solution achieved in such a way lacks scientific calculation and analysis [1,2].

CAE simulation technology helps practitioners generate, verify, validate and optimize the design solutions. In an aspect of product quality and defect prediction perspective, CAE simulation is a most technologically efficient and cost effective technology for analysis and evaluation of casting product quality and defects [3,4].

In this research, CAE was performed by using the simulation software (AnyCasting) in order to optimize casting design of an automobile part (Oil Pan on Fig. 1). Generally, oil pan is assembled on the below of the crank case and its purpose is to collect oil after a lubrication action conducted by oil pumper. The simulation results were analyzed and compared carefully in order to apply them into the production die-casting mold. During the filling process, air entrapments cause internal porosities that produce the defects of casting parts. They are usually occurred due to the non-uniform and vortex flow while filling the melt into the cavity of the mold. The flow junction zones (air entrapments) were predicted and reduced remarkably by the modification and the configuration of the gate system. The solidification shrinkage is usually occurred on the thick sections of a casting part and also causes other

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https://doi.org/10.1016/j.rcim.2018.01.003
Received 21 March 2017; Received in revised form 19 November 2017; Accepted 10 January 2018

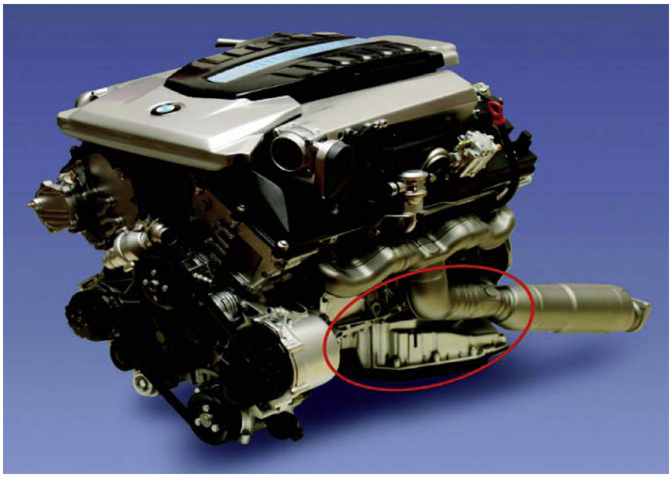

Fig. 1. Image of the engine module with Oil Pan [5].

porosity defects of a casting part. Internal porosities caused by the solidification shrinkage were predicted with the solidification analysis.

2. General die casting process

Die casting is a process in which the molten metal fills into the mold with the high pressure. The inverse of the part's shape basically consists of the cavity and core of the mold. Various casting production processes require the diverse physical property of the base material. The following six steps are the basic die casting process [3].

Step 1: The mold is open in the initial situation and ready for starting a new cycle.
Step 2: The mold is closed by moving the clamping system.
Step 3: The molten material is filled into the mold by the plunger (piston).
Step 4: The closed mold is hold until the material is solidified by the cooling system.
Step 5: The mold is open and the produced part is ejected by the eject pins.
Step 6: The blow stub clean and cool down the mold surface while the mold is open.

3. CAE simulation of die casting process

The commercial package (AnyCasting) was used to optimize a casting design before fabricating production HPDC mold. The software had been developed by AnyCasting Co., LTD. and employed a hybrid method mixing a PM (Porous Media) Method and a Cut-Cell Method that complements a drawback of the conventional FDM (finite difference method) rectangular mesh. The mold filling and solidification analysis are to be improved more accurate, and also calculation speed is improved more than 50% by decreasing mesh number [6]. Compared with several other commercial packages, AnyCasting has the ability to develop user friendly routines to describe dependent boundary conditions. As shown on Fig. 2, the process of CAE simulation with the package is described.

3.1. Numerical modeling of the casting process

The action (flow of the melted metal) in the HPDC process is the high pressure generated by the fast movement of plunge in the chamber. AnyCasting employed a hybrid method to analyze the flow of the melted metal and had been designed for analyze three-dimensional (3D) fluid flow with the free surface and boundary. The flow of the melted metal is considered any non-Newtonian and non-linear rheological properties. Making the modeling of the filling process, there are three phenomena (such as melt momentum balance, mass balance and energy balance) to be represented and modeled. The phenomena can be described by the following governing equations:

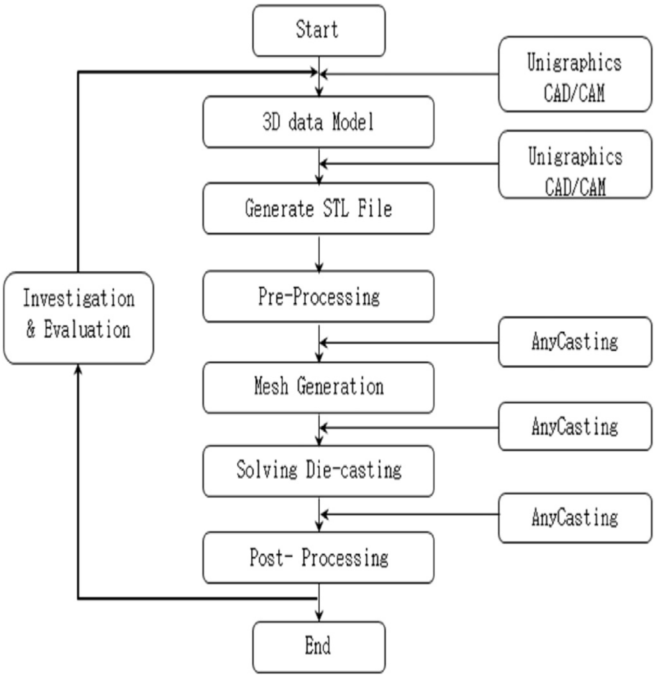

Fig. 2. Flow-Chart of die casting simulation.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j) = 0 \tag{1}$$

Momentum equation (Navier–Stokes):

$$\frac{\partial}{\partial t}(\rho U_i) + \frac{\partial}{\partial x_j}(\rho U_j U_i) = \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j}\right) + \rho g_i \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho C_p T) + \frac{\partial}{\partial x_j}(\rho C_p U_j T) = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right) + Q \tag{3}$$

Volume of Fluid (VOF):

$$\frac{\partial F}{\partial t} + U_j \frac{\partial F}{\partial x_j} = 0, 0 \le F \le 1 \tag{4}$$

where: *t*-time(s), *x*-space(m), *p*-density(Kg/m^3), *u*-kinematic viscosity(m^2/s), *g*-gravity(Kg f), C_p-heat capacity(J/K), *λ*-conductivity(W/m^2 K), *F*-volume(m^3), *U*-velocity(m/s), *T*-temperature(°C, K), T_s-solid temperature(°C, K), and *Q*-heat source(°C, K).

3.2. Geometry model of the casting process

The CAD models are created, and converted into STL format with Unigraphics (a commercial CAD/CAM package for product design and development) as shown on the flow chart in Fig. 2. AnyCasting imports directly the generated STL models for the filling and solidification simulation. As shown on Fig. 3, there are 3 different gate designs used for finding out the best result. The case 1 has 7 ingates and several overflows comparing with cases 2 and 3. In order to make a molten flow smooth around the pivoting block, the case 2 modifies the runner shape around it and also removes an overflow and line on the left side of the part. The case 3 has long tails on the end of the runner and six ingates comparing with cases 1 and 2, and also removes some overflows and changes their location on the right side of the part.

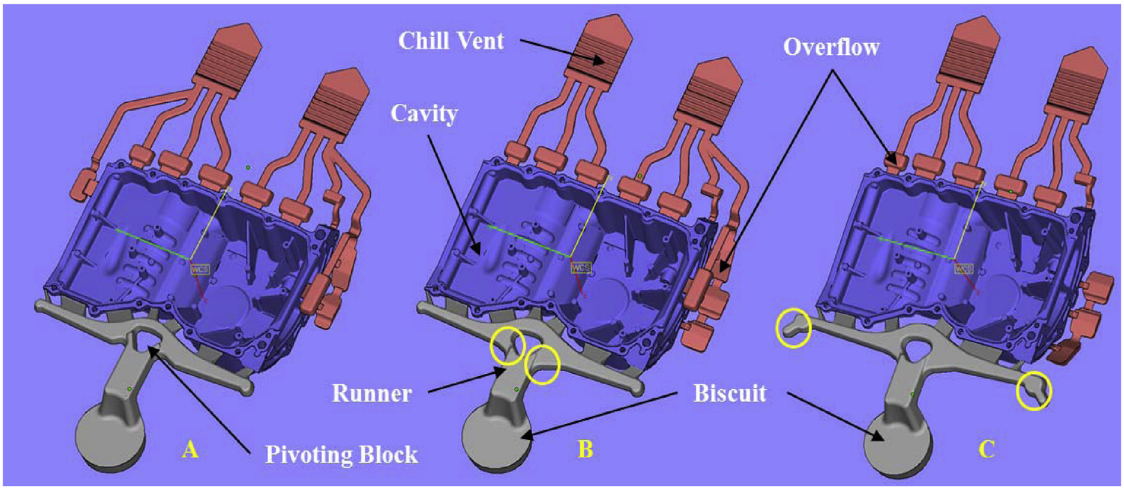

Fig. 3. Casting model of Oil Pan (BR2E). (A) Case 1, (B) Case 2, (C) Case 3.

Table 1
Chemical composition (%) of SKD61.

C	Si	Mn	P	S	Cr	Ni	Mo	V
0.32–0.42	0.80–1.20	<0.50	<0.03	<0.03	4.50–5.60	–	1.00–1.50	0.80–1.20
W	N	Cu	Co	Pb	B	Nb	Al	Other
–	–	–	–	–	–	–	–	–

Table 2
Condition for the CAE simulation.

Part		Mold		Plunger	
Material	ACD12	Material	SKD61	Diameter	120mm
Liquidus line	853.15K(580 °C)	Initial Temperature	473.15K(200 °C)	Slow velocity	0.90 m/s
Solidus line	788.15K(515 °C)	–	–	High velocity	3.50 m/s
Initial temperature	913.15K(640 °C)	–	–	Length	850 mm
Weight for casting	4083 g	–	–	–	–

3.3. *Pre-processing and mesh generation*

ADC12 ($AlSi_9Cu_3$) was used for the cast material and SKD 61 described on Table 1 was for the die material. Initial temperature and casting temperature for the cast material were 680 °C and 640 °C, respectively. Initial temperature and casting temperature for the mold were 200 °C and 280 °C, respectively.

The velocity of melt flow is an important parameter as it significantly affects the filling behavior and casting quality. In order to reduce the internal porosities of the casted part, generally, most volume of the cavity is filled during the time of slow shot [4]. The velocity and length of slow shot sleeve were 0.9 m/s and 660 mm, respectively. The velocity and length of fast shot sleeve were 3.5 m/s and 190 mm, respectively. In this case, 5% of cavity was filled by the slow shot. The size and volume of the part on Fig. 2 were 439 × 333 × 142 mm and 1,512,248 mm^3, respectively. The casting parts were meshed into 13.6million elements. In order to minimize the number of the elements, variable mesh type had been used instead of uniform mesh. Its type is rectangular shape and its size is variable.

3.4. *Simulation and post-process*

Casting simulation of each model had been conducted based on the given condition on Table 2 with AnyCasting. On the filling of the casting process, the melted material flows along the runner and enters into the cavity where the casting is molded. After the cavity is filled up, the extra melt, dirty metal and the air in the melt go into the overflow portion.

Fig. 4 presents the filling process and the position of the Melt Front Advancement (MFA) during the filling process. MFA describes the movement status of the melt flow and the arrival sequence in the filling processes [5]. It also shows the melt position for the given percentage of the filling. The flow phenomenon and defects can be revealed and identified with MFA. In addition, the last area to be filled up is usually the location of overflow which is the container of dirty melt and air [7–9].

On filling process shown on Fig. 5, cases 1 and 2 have non-uniform and worse flow and also have an isolated area. As shown on the Fig. 6, there are some surplus overflows and lines on cases 1 and 2. Those surplus features have to be removed in order to minimize the workload on the deburring process. The layout of cases 1 and 2 cannot be used for the proper tool design of this part.

According to the flow tracking on Fig. 7, filing volume of each ingate is described with colors on the part. As shown on Fig. 7(A), the size of ingate (G1) seems to be too big because the red color occupies most left side of the part. Its size has to be reduced to make a better flow balance. However, the size of ingate (G2) seems to be too small because the yellow color does not reach into the rear of the part. Its size has to be increased to make a better flow balance. The filling volume of ingate

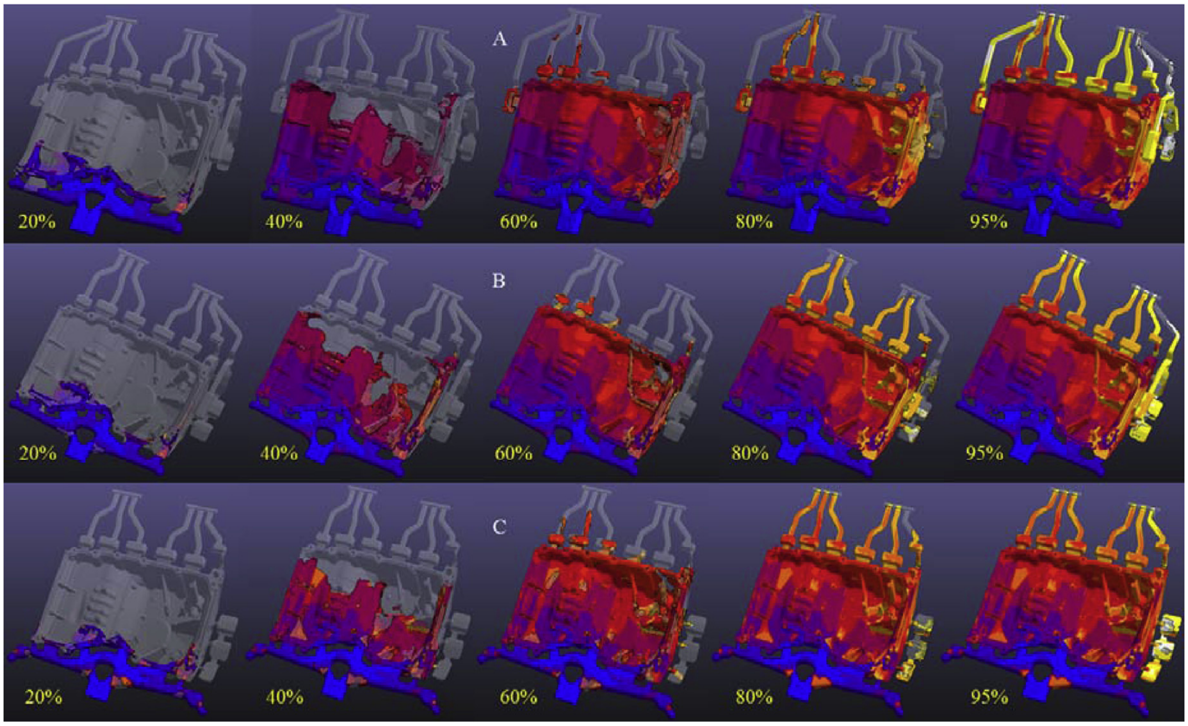

Fig. 4. Simulation results of the mold filling. (A) Case 1, (B) Case 2, (C) Case 3.

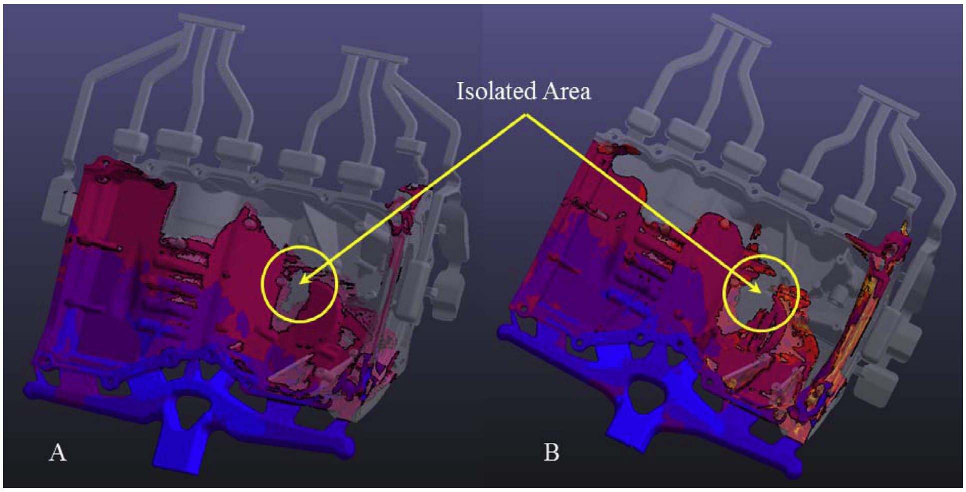

Fig. 5. Simulation results after 40% filling. (A) Case 1, (B) Case 2.

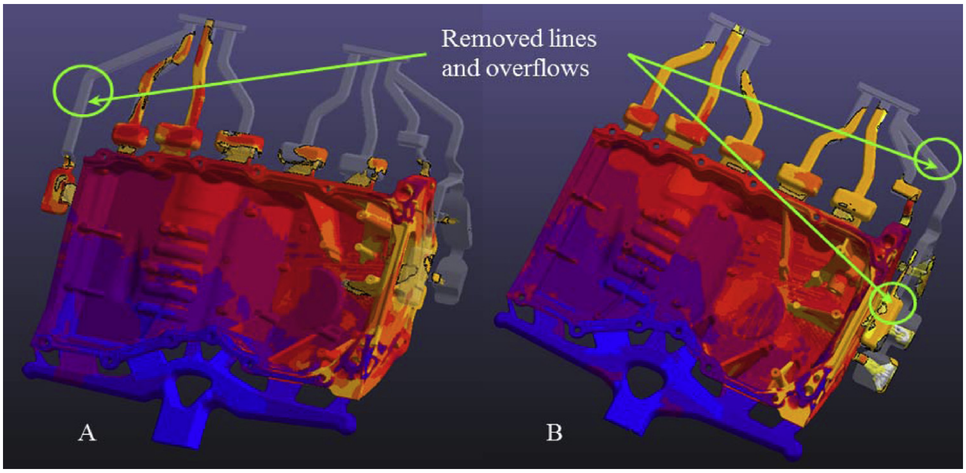

Fig. 6. Simulation results after 80% filling. (A) Case 1, (B) Case 2.

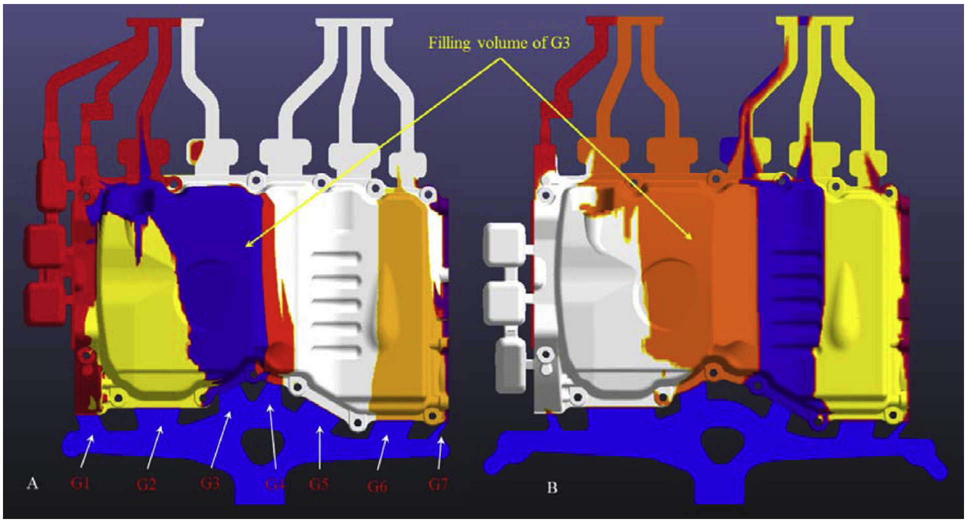

Fig. 7. Flow tracking of each ingate. (A) Case 2, (B) Case 3. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

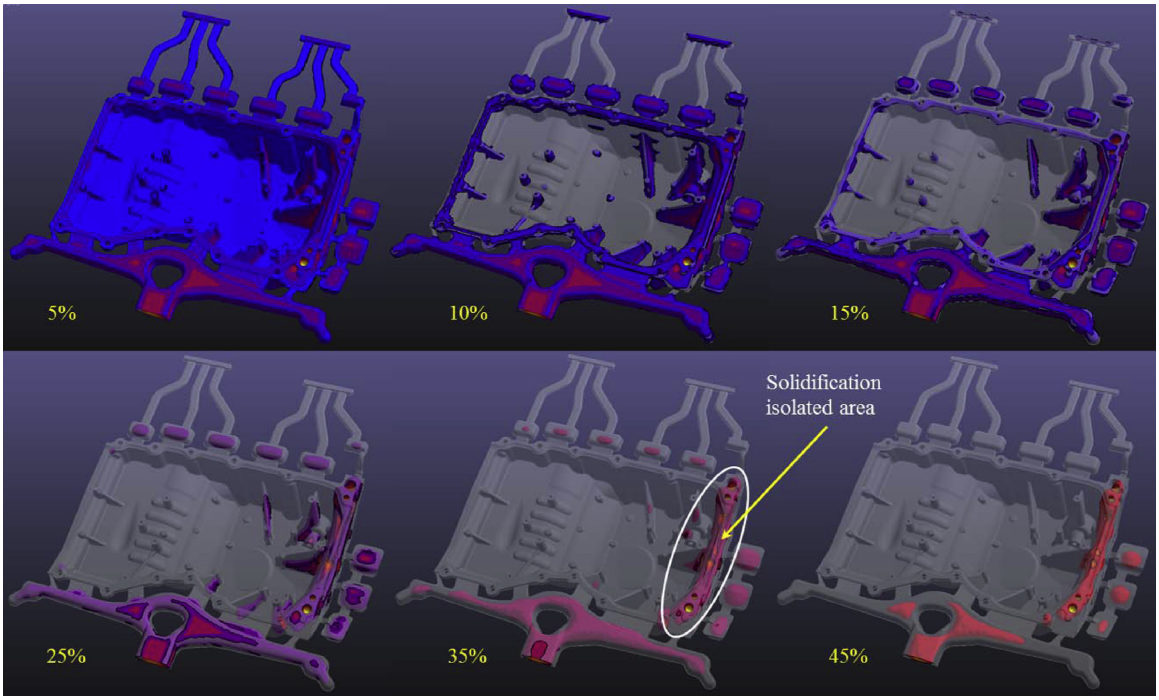

Fig. 8. Simulation results of the solidification with Case 3.

(G4) is too small and it seems to be not useful on the gate layout. By the time, the size of ingate (G5) seems to be too big because the white color occupies most right side of the part. Its size has to be reduced to make a better flow balance. The gate layout on Fig. 7(B) has been designed again based on the flow tracking result of case 2. The gate layout of case 3 has much better flow balance according to the flow tracking result on Fig. 7. And also it has a better uniform flow shown on Fig. 3(C).

The solidification with case 3 is conducted after finishing the filling process. The solidification result is used to identify and determine areas of excessive shear heating in thick areas or excessive cooling in thin areas. Ideal result shows uniform temperature distribution. Usually, the thick area contains a lot of heat and presents the hottest areas which are the last solidification area [7–9]. As shown on Fig. 8, isolated areas are detected on the right side of the part by the simulation result of solidification. Due to the solidification, shrinkage defects might be occurred on those areas.

Fig. 9 shows the section of the expected defect areas occurred by the solidification shrinkage. The shrinkage defect areas are observed with the modulus method in AnyCasting package. According to our past tooling experiments, the shrinkage was occurred on those areas due to ununiformed cooling temperature. In order to prevent those defects, sophisticated cooling system on those areas has to be added when the mold is fabricated. With the cooling system, uniform temperature can be achieved during the solidification.

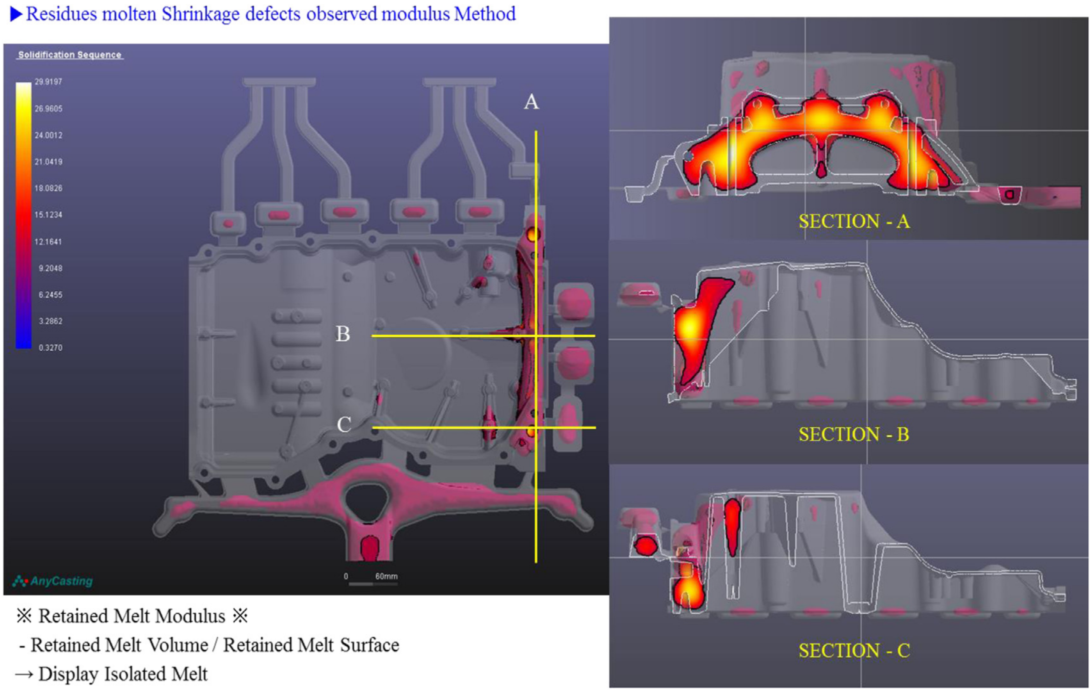

Fig. 9. Expected shrinkage defect areas of Case 3.

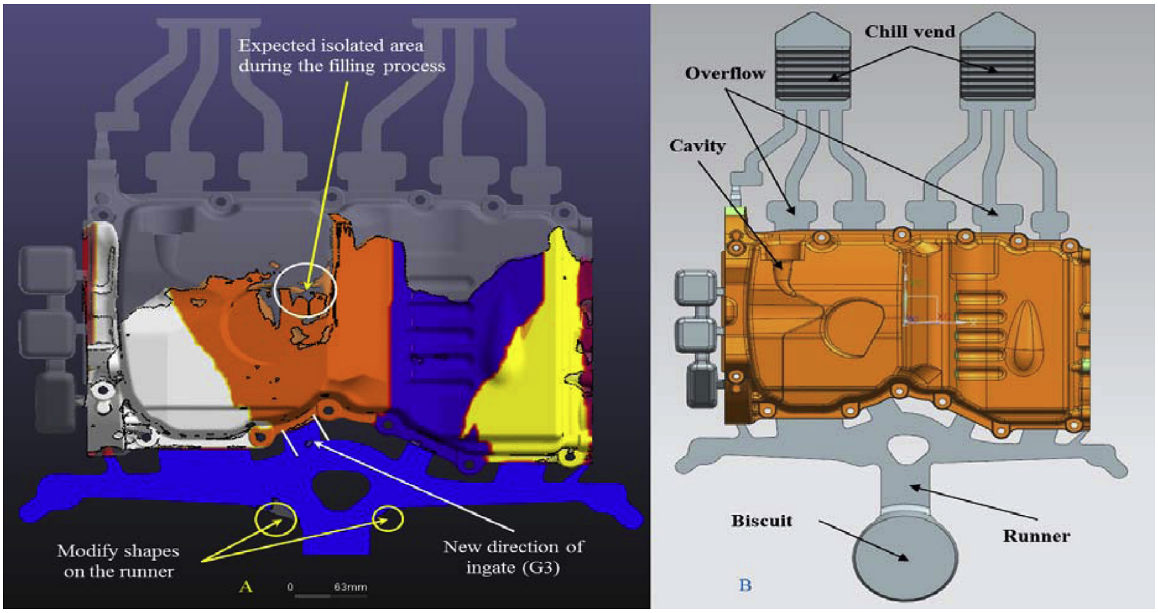

Fig. 10. (A) Simulation results after 40% filling of case 3; (B) Final casting layout.

4. Results and discussion

By comparing the simulation results in the points of the filling process and solidification, the casting design with case 3 produces much better results. But there are some improvements existed on case 3 according to the simulation results. As shown on Fig. 10(A), an isolated area is expected on the middle of the part while filling up the melted material into the cavity of the mold. In order to prevent the porosity defects on those areas and make the better melt flow, direction of ingate (G3) might be changed shown on Fig. 10(A). There are some vortex areas detected around the pivoting block. Those vortex areas have to be removed or modified to improve the molten flow on the runner. Some modifications have to be applied on the shapes around the pivoting block on Fig. 10(B).

The final casting design has been modified shown on Fig. 10(B). Simulation results on Fig. 11 has a better flow direction and also better uniform flow comparing with the simulation results of other three cases. In order to fabricate a production HPDC mold, the final casting design is applied into the mold layout for producing a better quality parts.

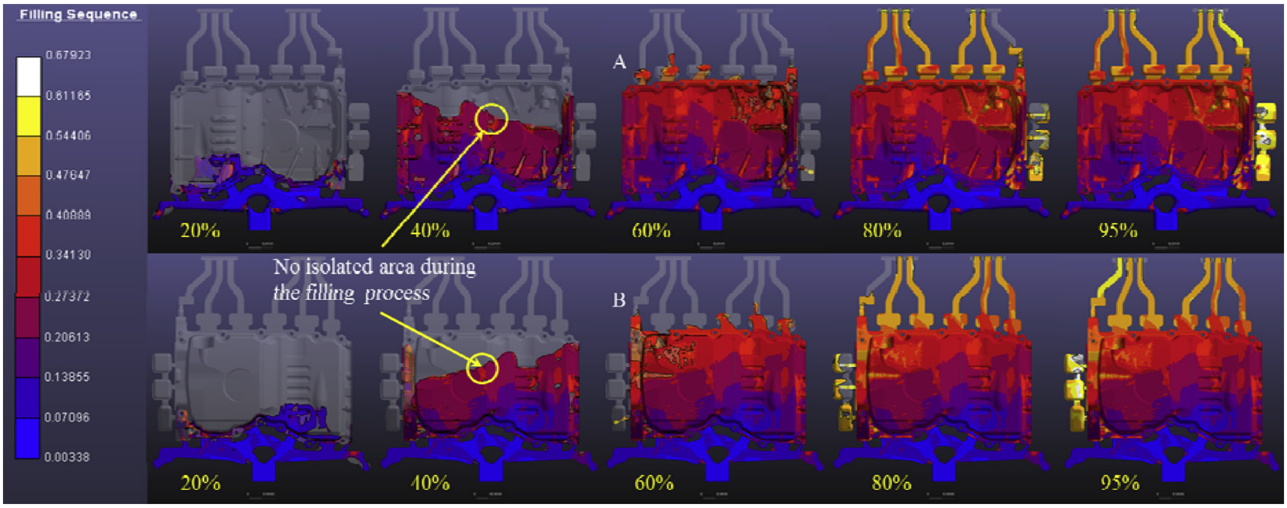

Fig. 11. Simulation results with the final tool design. (A) View of the moving side, (B) View of the fixed side.

5. Conclusions

In current casting industries, the design and development of a casting product and process are a trial-and-error process based on heuristic know-how [9,10]. The solution achieved in such a way lacks scientific calculation and analysis. Using CAE simulation with AnyCasting, the following results had been achieved:

- According to the filling process, the final casting layout on Fig. 10(B) is better than other casting layouts on Fig. 3 because of the location of the flow junction zone, and the uniform and even filling into the mold cavity. Based on several simulation results and analysis, the final casting layout had been designed by a special experienced tooling designer.
- The pivoting block on the runner center is useful concept to prevent any backflows generated on the entrance area to be filled up. And also, the chill vent is useful concept to absorb the entrapped airs generated on the last area.
- As shown on Fig. 9, the shrinkage defect areas are observed with the modulus method. The heat-shrink is occurred on those areas due to ununiformed cooling temperature and causes the shrinkage defect from our past tooling experiments. In order to prevent those defects, sophisticated cooling system on those areas has to be added when the mold is fabricated. By applying the final casting design on Fig. 10(B) into a production HPDC mold, the simulation results on Fig. 11 has to be verified.

Acknowledgment

Funding for this paper was provided by Namseoul University.

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