Process Design Optimization through Numerical Experimentation for a Brake Disc Casting

Chun-Ping Yeh\textsuperscript{1,*1}, Weng-Sing Hwang\textsuperscript{1,*2} and Chien-Hen Lin\textsuperscript{2}

\textsuperscript{1}Department of Materials Science and Engineering, National Cheng Kung University, Tainan 701, Taiwan, R.O. China
\textsuperscript{2}China-Motor Corporation Co. Ltd., Taoyuan 326, Taiwan, R.O. China

An integrated numerical model is applied to simulate the mold filling and solidification phenomena as well as to predict the occurrence of the related casting defects for a brake disc casting. The goal is to conduct numerical experimentation to improve the running and gating system of the brake disc casting to obtain better casting quality. A computer-aided engineering software based on the finite element method is employed in this study. Numerical simulations are conducted for the brake disc casting with a preliminary running and gating system. The mold filling and solidification phenomena are examined to predict the occurrence and extent of the casting defects. They are found to be consistent with the defects observed in the actual casting. Based on the findings of the simulated results, a modified running and gating system is then proposed. The mold filling and solidification phenomena for the modified design are simulated. The results show that the problem of casting defects is alleviated with use of present results. [doi:10.2320/matertrans.MRA2007233]

(Received October 2, 2007; Accepted February 21, 2008; Published April 2, 2008)

Keywords: sand casting, mold filling simulation, solidification simulation, casting defect

1. Introduction

Brake discs are mostly manufactured by the sand casting process. For sand casting process, casting defects such as shrinkage porosity and hot tear are often found. The formation and distribution of these defects are greatly affected by the casting geometry as well as running and gating systems. A poorly designed running and gating system may lead to incomplete filling, inadequate feeding of the volumetric shrinkage, entrapped inclusions, and dissolved gas. To eliminate these problems, proper design of running and gating system is of great importance.

However, the opacity of the mold and high temperature of the molten metal during casting process make it difficult to be observed. Trial and error practices to obtain optimal design are expensive and time-consuming. Simulation of casting process aims to help the foundry engineers to optimize the design by better understanding of the temperature history of the solidifying casting. The simulated results can be used to obtain defect free casting in a systematic way.

Several studies have been conducted on the numerical simulations of mold filling and solidification process. Shepel \textit{et al.} modeled filling and solidification of an automotive piston casting of aluminum alloy.\textsuperscript{1)} They modeled the mold filling process using the volume-of-fluid (VOF) method. Zhou \textit{et al.} used an engineering software to simulate the mold filling process of aluminum alloy and zinc alloy high pressure diecasting. They optimized the process design through numerical experimentation.\textsuperscript{2)} Youn \textit{et al.} used an engineering software to analyze the die filling and solidification phenomena for an engine mounting bracket casting, which is an automobile part.\textsuperscript{3)} Yan \textit{et al.} modeled filling and solidification of an automobile plug casting of AZ91D magnesium alloy.\textsuperscript{4)} They proposed a modified scheme according to the simulated results to reduce the casting defects. Sulaiman \textit{et al.} modeled temperature history for a sand casting with 2-ingate mold and 3-ingate mold.\textsuperscript{5)} They found that experimental results are higher than the simulated ones because of the entrapped gas effect. Li \textit{et al.} used an engineering software to conduct numerical modeling for the mold filling and solidification processes of a new designed golf putter of 17-4 stainless steel.\textsuperscript{6)} They made modification to optimize the process design accordingly.

In this study, an integrated numerical model for brake disc is presented. The purpose of this study is to optimize the design of the running and gating system through numerical experimentation with this simulation tool.

2. Numerical Model

2.1 Description of the physical system

In this study, a computer simulation system; ProCAST, is employed to simulate the metal flows in a brake disc casting with different running and gating systems.\textsuperscript{7)} A graphics of the brake disc is shown in Fig. 1. The diameter of the brake

---

\*1 Graduate Student, National Cheng Kung University
\*2 Corresponding author, E-mail: wshwang@mail.ncku.edu.tw

Fig. 1 Shape and dimensions of a brake disc casting.
disc casting is 276 mm and the diameter of the inner hole is 71 mm.

This simulation system is based on the finite element method and the whole physical system, which includes the casting, running system and gating system, is subdivided into tetrahedron elements. FC250 gray cast iron is selected as the casting alloy. The solidus temperature of FC250 gray cast iron is 1100°C. The casting is made with a silica sand mold and the preheat temperature of the mold is 45°C. The pouring temperature is 1450°C and the pouring time is around 12 seconds. The ambient temperature surrounding the casting is around 40°C.

2.2 Criteria for determining casting defects

In foundry practice, the hot spot concept is frequently used to predict and determine if there will be defects in a casting. Hot spots are normally the last sections to solidify compared to those which surround them. Evaluation of the last solidified regions is done by finding out which place needs the longest time to reach the solidus temperature and observing if the surrounding regions have already solidified.

The way to predict shrinkage porosity is to use the variation of solidification fraction. Shrinkage porosity mostly occurs in the two-phase region where solidification is almost completed. When the fraction of solid is larger than 0.7, the feeding behavior of the remaining melt is like liquid flowing in a porous media.5 With the temperature decreasing, the increase of the melt viscosity makes it difficult for the melt to flow in the porous media to feed the shrinkage due to solidification. Thus, pores occur in these regions.

Another method to predict shrinkage porosity is to calculate fluid pressure in the casting during the course of solidification. This method can evaluate quantitative amount of casting defects. If the pressure drops below the cavitation pressure, it is then assumed that liquid feeding has ceased and that the solidification shrinkage in the computational cell is compensated only by pore growth. Therefore porosity can be determined for the entire casting. The computational cycle is as follows:

1. Solve the energy equation and obtain the temperature field and fraction of solid.
2. Solve the pressure from the momentum equation without considering porosity.
3. Calculate the gas concentration in the liquid and solid.
4. Compute the gas pressure.
5. Solve for pressure by taking into account of porosity.
6. Compute the pore fraction and update volumetric fractions and pressure. It is iteratively calculated within a time step until convergence.

3. Results and Discussion

Results of the simulation are analyzed and presented with the help of graphical tools. The filling and solidification process will be discussed. The prediction of defects utilizes the concepts of hot spot and fraction of solid.

3.1 Preliminary design

The disc casting cavity includes an upper disc casting cavity located at the cope flask and a lower disc casting cavity located at the drag flask. The two cavities are separated by a middle plate core. The preliminary design of the running and gating system includes a vertical sprue, a rectangular shape horizontal runner, a connecting plate runner and runners which extend from the plate runner and include two symmetrical parts surrounding the disc casting. The runners which surround the two sides of the casting are half-circular in shape. Four ingates are connecting the runners and the casting on both sides of the casting with two upper ingates to feed the upper disc casting cavity and two lower ingates to feed the lower disc casting cavity.

3.2 Simulation results of the preliminary design

Figure 2 shows the emmeshed solid model of a brake disc casting. The length, height and depth of the simulated system are 700, 600 and 484 mm, respectively. The total number of nodes and elements used for the simulation is 302,389 and 1,464,662, respectively.

Simulation results of the filling stages for the lower disc are illustrated in Fig. 3. It can be seen from Figs. 3(a) and 3(b) that the melt flows into the right part of the lower disc earlier than the left part. Figures 3(c) and 3(d) show the filling patterns in the lower disc casting at 3.18 seconds and 4.48 seconds, respectively. Figure 3(e) shows that the filling from the four ingates are not homogeneous. It indicates that the mold cavity is not filled smoothly and evenly. The lower disc is completely filled in 8.89 seconds as shown in Fig. 3(f).

Simulation results of the filling stages for the upper disc are illustrated in Fig. 4. From Figs. 4(a) and 4(b), it can be observed that the flow of the right part runner is much quicker than the left part runner, which is similar to the filling phenomena as the lower disc. Figure 4(c) shows the filling pattern in the upper disc casting at 8.93 seconds. The upper disc is completely filled in 12.0 seconds as shown in Fig. 4(d).

Side view of the filling stages of the brake discs, which include the lower disc and upper disc, are illustrated in Fig. 5. It reveals clearly the filling sequence of the brake discs. The columnar part is filled faster than the other part.
Fig. 3  Filling patterns and temperature profiles of the lower disc during filling with the preliminary design.

(a) 1.74 seconds  (b) 2.10 seconds  (c) 3.18 seconds

(d) 4.48 seconds  (e) 4.72 seconds  (f) 8.89 seconds

Fig. 4  Filling patterns and temperature profiles of the upper disc during filling with the preliminary design.

(a) 4.48 seconds  (b) 6.76 seconds  (c) 8.93 seconds

(d) 12.0 seconds

Fig. 5  Side views of the filling patterns and temperature profiles of the disc during filling with preliminary design.

(a) 3.80 seconds  (b) 6.04 seconds  (c) 9.14 seconds
of the disc as shown in Figs. 5(a) and 5(b). It can also be seen from Fig. 5(b) that the upper disc starts to be filled when the lower disc have not been filled completely. Figure 5(c) shows the side view of the filling pattern in the brake disc casting at 9.14 seconds. Figure 6 shows the temperature profiles during solidification stages. Figures 6(a)–(c) represent the temperature profiles of the upper disc casting and Figs. 6(d)–(f) represent the temperature profiles of the lower disc casting. It should be noted that the lower disc casting is actually presented upside down of the actual arrangement. It can be seen from Fig. 6(a) that the last region to be solidified for the upper disc casting is located near the upper-right ingate. Figure 6(b) shows the temperature profile of the upper disc casting at 713 seconds. Figure 6(c) shows the upper disc is entirely solidified at 818 seconds. From Fig. 6(d), it can be observed that the last region to be solidified for the lower disc casting is located near the upper-right ingate. Figures 6(e) and 6(f) show the temperature profiles of the lower disc casting at 713 seconds and 803 seconds, respectively. Figure 6(f) shows that the lower disc casting is fully solidified at 803 seconds.

The solid fraction profiles of the discs during solidification are represented in Fig. 7. Figures 7(a)–(c) represent the solid fraction profiles of the upper disc casting and Figs. 7(d)–(f) represent the solid fraction profiles of the lower disc casting. The distribution of solid fraction is presented by different scales from 0 to 1. Figures 7(a) and 7(b) show the solid fraction profiles of the upper disc casting at 213 seconds and 323 seconds, respectively. From Fig. 7(c), it can be observed that the last region to be solidified for the upper disc casting is located near the upper-right ingate. Figures 7(d) and 7(e) show the solid fraction profiles of the lower disc casting at 258 seconds and 383 seconds, respectively. Figure 7(f) shows that the lower disc casting has the similar results. It can be predicted that defects may be highly likely to appear in those areas.
3.3 The modified design

In this study, numerical experimentations are carried out to optimize the running and gating systems. The simulation results of the preliminary design show that the metal flow from the right side runner is earlier to fill the mold cavity than the left side runner. It leads to an inhomogeneous situation where the melt enters the ingates on the two sides at different times. To improve the mold filling conditions, the running and gating system has to be modified. The upper-right corner of the horizontal runner is cut off from a straight rectangular runner to a ladder-shaped runner. This modification decreases the right part volume of the horizontal runner which can decrease the melt flow speed in the right side runner. With this design, it is anticipated that the flow speeds of the melt in both part runners can be balanced, which makes the filling behavior smoother.

3.4 Simulation results of the modified design

The total numbers of nodes and elements used for the simulation are 301,092 and 1,457,280, respectively. Simulated results of the filling sequences for the lower disc casting are illustrated in Fig. 9. It can be observed from Figs. 9(a) and (b) that the time difference for the melt to enter both upper-right ingate and upper-left runner is 0.11 second, which is considerably shorter than the 0.46 second required for the preliminary design. Figure 9(c) shows the filling pattern in the lower disc casting at 2.17 seconds. It can be observed that the filling from the four ingates is more homogeneous in Fig. 9(d) than that shown in Fig. 3(d). Figure 9(e) demonstrates that the mold cavity is filled rather smoothly and evenly. At 6.86 seconds, the filling process of the lower disc is completed as shown in Fig. 9(f).
Simulation results of the filling sequences for the upper disc are illustrated in Fig. 10. From Fig. 10(a), it reveals that the melt enter the four ingates simultaneously, which indicates a smoother mold filling. Figure 10(b) shows the filling pattern in the upper disc casting at 8.16 seconds. The upper disc is entirely filled in 11.8 seconds as shown in Fig. 10(c).

Side views of the filling sequences for the brake discs are illustrated in Fig. 11. The flow patterns show that the mold filling process is steady and the upper disc starts to be filled only after the lower disc is completely filled as shown in Figs. 11(a) and 11(b). Figure 11(c) shows the side view of the filling pattern in the brake disc casting at 7.95 seconds.

Figure 12 shows the temperature profiles during the solidification stage. Figures 12(a)–(c) represent the temperature profiles of the upper disc casting and Figs. 12(d)–(f) represent the temperature profiles of the lower disc casting. It can be seen from Fig. 12(a) that the last region to be solidified for the upper disc casting is still located near the upper-right ingate. However, it is much smaller compared to that shown in Fig. 6(a), which implies that the defects may be reduced. Figure 12(b) shows the temperature profile of the upper disc casting at 636 seconds. Figure 12(c) shows the upper disc casting is completely solidified at 726 seconds which is shorter than the preliminary design by 92 seconds. From Fig. 12(d), it reveals that the last region to be solidified for the lower disc casting is also located near the upper-right ingate. Similarly, it is much smaller compared to that shown in Fig. 6(d). Figure 12(e) shows the temperature profile of the lower disc casting at 607 seconds. Figure 12(f) shows the lower disc casting is fully solidified at 662 seconds which is shorter than the preliminary design by 141 seconds.

Figure 13 shows the solid fraction profiles at different solidification stages. Figures 13(a)–(c) represent the solid fraction profiles of the upper disc casting and Figs. 13(d)–(f) represent the solid fraction profiles of the lower disc casting. Figures 13(a) and 13(b) show the solid fraction profiles of
the upper disc casting at 191 seconds and 256 seconds, respectively. At 421 seconds, as shown in Fig. 13(c), the last region to be solidified for the upper disc casting is located near the upper-right ingate. It can be noted that the last solidified section is smaller compared to that shown in Fig. 7(c). Figures 13(d) and 13(e) show the solid fraction profiles of the upper disc casting at 222 seconds and 327 seconds, respectively. Figure 13(f) demonstrates the resembling result as well.

Figure 14 shows the shrinkage porosity profiles of the disc casting with the modified design. Figure 14(a) shows the shrinkage porosity profile of the upper disc casting and Fig. 14(b) shows the shrinkage porosity profile of the lower disc casting. It can be seen from Figs. 14(a) and (b) that no shrinkage porosity can be detected in both the upper and lower disc castings.

4. Conclusion

In this study, a computer-aided engineering software is used to evaluate the occurrence of casting defects under various running and gating designs for the sand casting of brake disc. Two types of running and gating designs are examined through numerical experimentation and a proper design can be obtained through this process.

(1) A preliminary design of running and gating system for the disc casting results in an inhomogeneous feeding through the various ingates. With temperature gradient and solid fraction methods, porosity is found near the upper-right ingate for both the upper and lower disc castings. For the modified design, the porosity occurrence has been significantly reduced.
A pressure calculation method has also been adopted to predict the occurrence of casting defects in this study. It predicts that for the preliminary design nearly 4% of the area near the upper-right and upper-left ingates in the upper disc casting and nearly 65% of the top surface in the lower disc casting is covered with porosity while no detectable porosity can be found in both upper disc and lower disc castings with the modified design.

Acknowledgements

The authors would like to thank China-Motor Corporation and National Science Council (NSC 95-ET-7-006-005-ET) in Taiwan for their financial support of this study.

REFERENCES


Fig. 14  Shrinkage porosity profiles of the disc casting with the modified design ((a): upper disc casting, (b): lower disc casting).