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DESIGN OF THE FILLING AND FEEDING SYSTEM OF GRAY CAST IRON PARTS THROUGH NUMERICAL SIMULATION

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Abstract. Defects are a common problem in casting parts due to the multiple mechanisms and many process variables that can cause them. Gray cast irons are susceptible to most of the most common defects of this type of process, some of them being the cold shut defects and misruns, which usually occur in part sections with large areas and thin walls, due to the loss of temperature and filling pressure of the liquid metal. These defects are strongly related to the adopted feeding system and can be avoided by changing the geometry of the attack channels. With technological advances and the development of numerical simulation software, it is possible to predict the metal behavior during filling and solidification in the casting process, which enables the design of optimized filling and feeding systems. This work, performed in a metallurgical company in Santa Catarina, analyzed defects in a grey cast iron FC-200 product obtained by the PUNB (Phenolic Urethane No Bake) molding process, aiming to identify the causes and propose solutions for the problems. With the aid of MAGMA casting software, the temperature and velocity distributions of the metal during the filling of the part were analyzed in order to obtain solutions to avoid defects. A first version of the mold design was simulated, and based on the observed results, two other versions in sequence were too until solving the filling and feeding system and avoiding the defects, as verified through the application of the proposals in the manufacturing of test parts submitted to analyses.

Keywords: Gray cast iron; Cold shut; Feeding system; Casting mold design; Casting design using FEM.

1. INTRODUCTION

For over 6,000 years, the casting process has been known as a manufacturing method. Currently, its importance is given in the main sectors of the economy, such as the automotive, machinery and equipment, energy, railway, mining, and agricultural sectors. In Brazil in 2019, more than 2 million tons of castings were produced, making the country the 10th largest castings producer worldwide (Modern Casting, 2021). Despite being a well-known process, it still faces difficulties in quality control and production efficiency regarding energy and raw material consumption. According to Lei *et al.* (2019), most foundry defects and inefficiencies originate from the filling or solidification process, and the geometry of the foundry system strongly influences these processes. As a result, the filling and feeding systems must be modified in order to reduce or even eliminate casting defects.

Developing a filling and feeding system by trial and error method takes too much time, cost, and workforce. In contrast, numerical simulation has been used as an essential tool in decision-making in manufacturing industries, allowing to model of a system or process to examine the different physical phenomena during the foundry processes, aiming to optimize from the design process to the foundry parameters to reduce defects, use less energy and therefore improve casting quality and productivity (Ayar *et al.*, 2020).

This work aims to demonstrate how a commercial FEM software (MAGMA) can be used to design a filling and feeding system for a casting, by analyzing the velocity and temperature distributions during filling, aiming to avoid the appearance of defects such as cold shut, burnt-on sand, and inclusion of sand. The part object of the study is an electric motor cover manufactured in FC-200 gray cast iron, with the mold obtained by the PUNB (Phenolic Urethane No Bake) process.

2. PROBLEM DEFINITION

This work was carried out in the foundry sector of a Brazilian electric motor manufacturer, based on the CAD project modification of the filling and feeding system in the casting of an electric motor fan cover. The part is manufactured in grey cast iron FC-200, following the ABNT NBR 6589: 1986 standard.

The studied casting has approximate dimensions of 600 mm in diameter, 500 mm in height, and an approximate thickness of 8 mm, with a mass of 38 kg. The sand molds are produced by the PUNB (Phenolic Urethane No-Bake) molding process. Currently the mold to produce this item is split into two halves, and the mold cavity is fed through two 20 ppi ceramic sponge filters positioned in the fill and feed system. The pouring temperature is within the range of 1410 to 1440 °C.

The metal flow in filling the parts cavities occurs from bottom to top, with four runners (2 for each casting part) and 20 gates (10 for each casting part), as shown in Figure 1(a) and the schematic drawing of Figure 1(b). The system is depressurized, i.e., runners and gates areas are greater than or equal to the cross-sectional area of the down sprue.

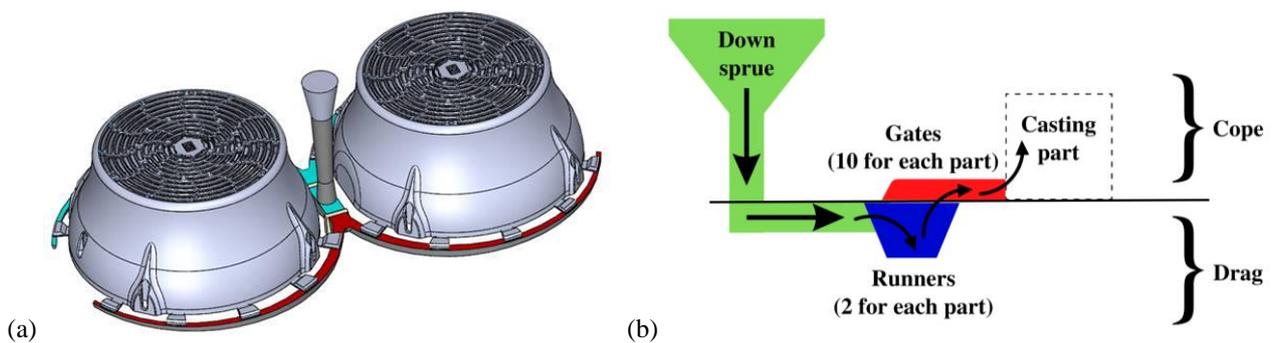


Figure 1. Original part design of the filling and feeding system (a) 3D; (b) schematic drawing.

The high ratio between the cover area and its thin thickness fosters the appearance of cold shuts and misruns (Figure 2) due to the loss of pressure and temperature of the metal during the filling of the part walls, causing the metal to solidify prematurely.

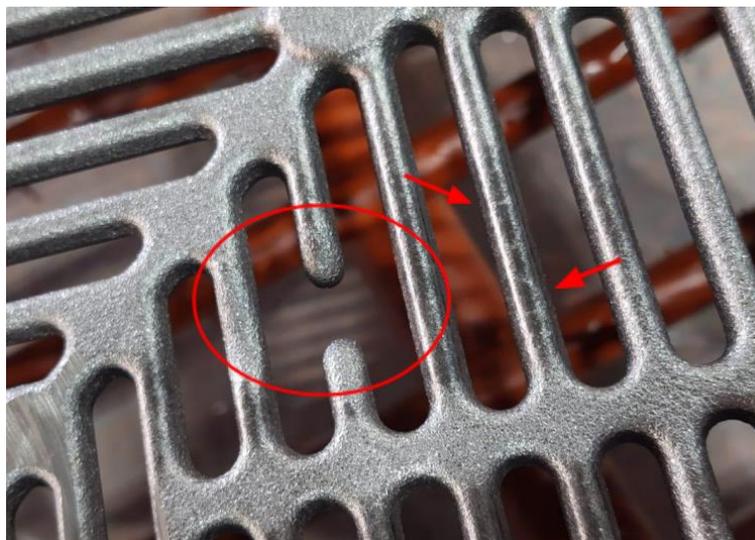


Figure 2. Cold shut and misruns defects in the casting part.

Moreover, the positioning of the gates in the cope makes it difficult to compact the molding sand since there is little space left to be filled with sand, creating a thin sand wall with poor consolidation. Thus, during the part filling, portions of sand detach from the mold, causing inclusions, metallic penetration, and burnt-on sand (Figures 3 (a) and (b)).

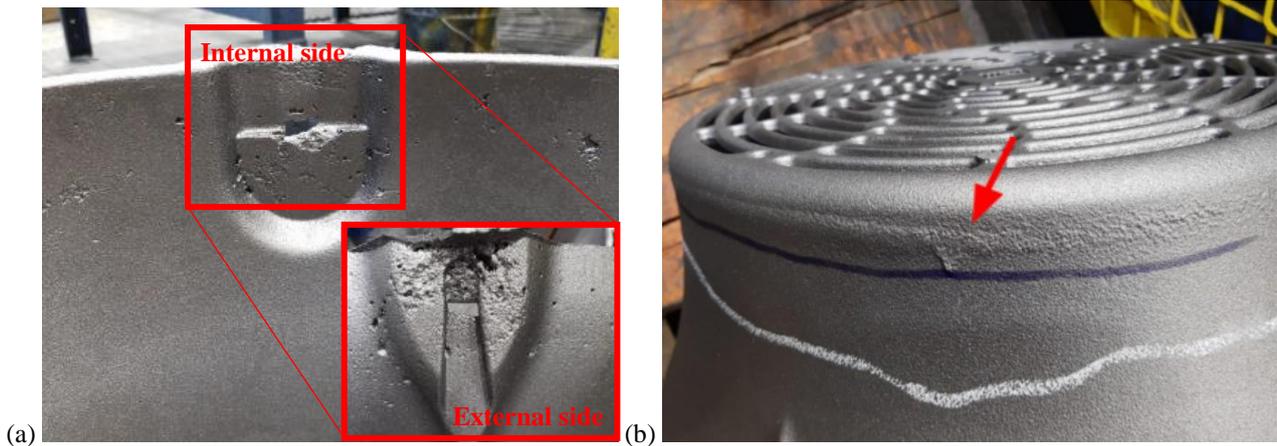


Figure 3. (a) Defects from sand inclusions and surface flaws due to sand erosion in the mold fill; (b) Burnt-on sand defect due to poor consolidation.

3. METHODOLOGY

In casting simulation, mold filling and solidification analysis were done using a commercial finite element-based simulation software to analyze 3D models of castings and identify hot spots and defects. These software involve sophisticated functions for user interface, computation, display and deliver different results with different objectives (distributions of temperature, filling velocities and air pressure). The casting mold model (with its filling and feeding system) must be created using a CAD solid modeling software and imported into the simulation program (Debade and Bhedasgaonkar, 2013).

Process variables such as the pouring temperature of the molten metal, the time required to feed the casting part into the production line, and the type of alloy material used are user-defined within the software. And, after setting the parameters, tolerances, and number of elements in the software to discretize the casting part, considering the software processing time and the capacity of the computer used, the software generates the sand mold to begin the simulation automatically. Figure 4 shows the steps involved in simulating the casting process.

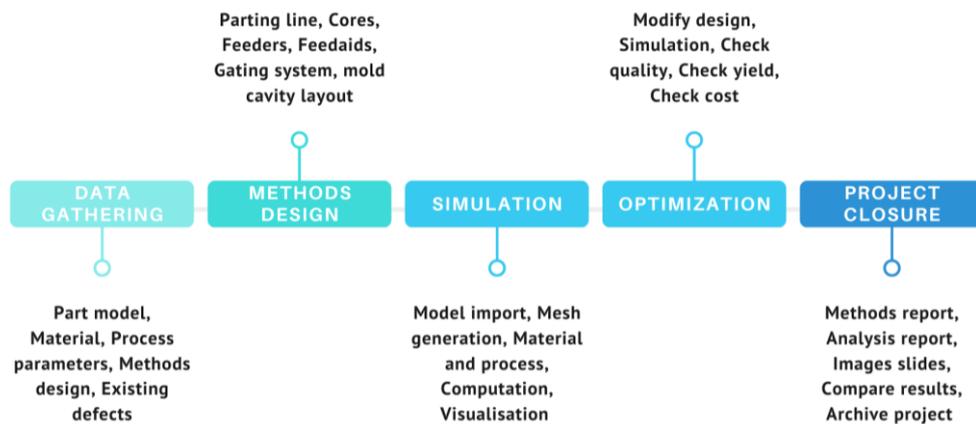


Figure 4. Casting simulation-optimization methodology (adapted from Debade and Bhadasgaonkar, 2013).

This study was carried out from the problem identification and definition on the shop floor, with subsequent modeling of the 3D project in Solid Works and imported into the numerical simulation software MAGMA for analysis of temperature and filling velocities, ending with preliminary practical tests for final design validation.

4. RESULTS AND DISCUSSION

Simulation analysis for the original filling and feeding system demonstrated a massive temperature loss in the metal as it reached the fan cover grids. With the pouring temperature between 1410 and 1440 °C, it can be seen in Figure 5(a) that the metal gets the grids between 1207 and 1213 °C, i.e., there's a metal temperature drop of more than 200 °C. This is because the air inside the mold resists the upward vertical filling of the liquid metal (Figure 5(b)), which decreases the

filling velocities, thus giving more time for the metal to lose temperature, which favors its early solidification and leads to the previously mentioned defects: cold shut and misruns.

Based on this analysis, proposals were made to improve the feeding and filling system design, as discussed below.

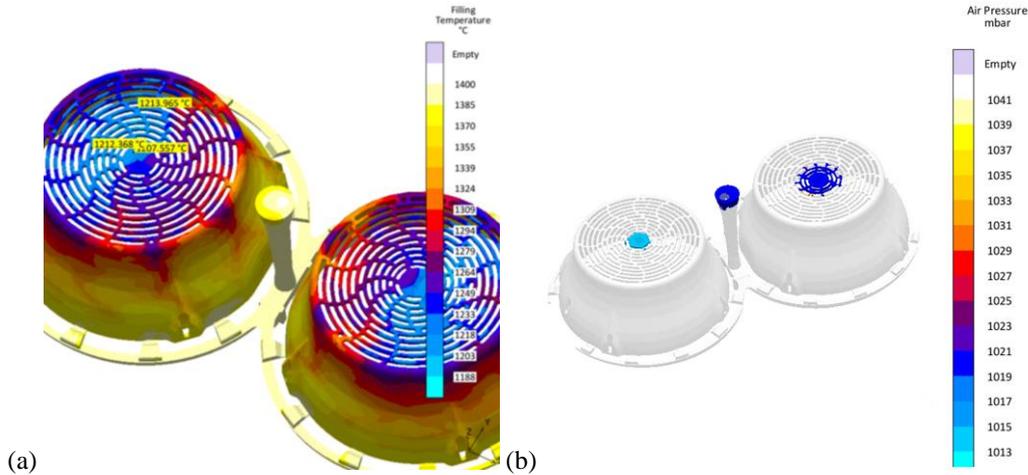


Figure 5. Original part design filling and feeding system analysis of (a) temperature; (b) air pressure.

4.1 Design I

In the project of Design I, a simple inversion of the direction of the feeding system and the casting part was made, with the gates quantity reduction and the increase of the gates cross-sectional area. The down sprue was repositioned from the center to one of the sides of the feeding system, which made it possible to eliminate one ceramic filter. The runners (2 for each casting part) and the gates (4 for each casting part) were kept in opposite partitions of the mold, now with the runners in the cope and the gates in the drag. There was no change in the total area of the gates, so the system was kept depressurized. Figure 6(a) shows the 3D project of Design I, and Figure 6(b) shows the mold parting line and the path taken by the liquid metal during feeding.

With the position inversion of the casting part, there was a shortening of the down sprue since the height of the flask, and the rest of the mold remained the same, with changes made only to the feeding system. This could lead to a loss of filling pressure, but this problem does not occur because the filling flow takes advantage of gravity.

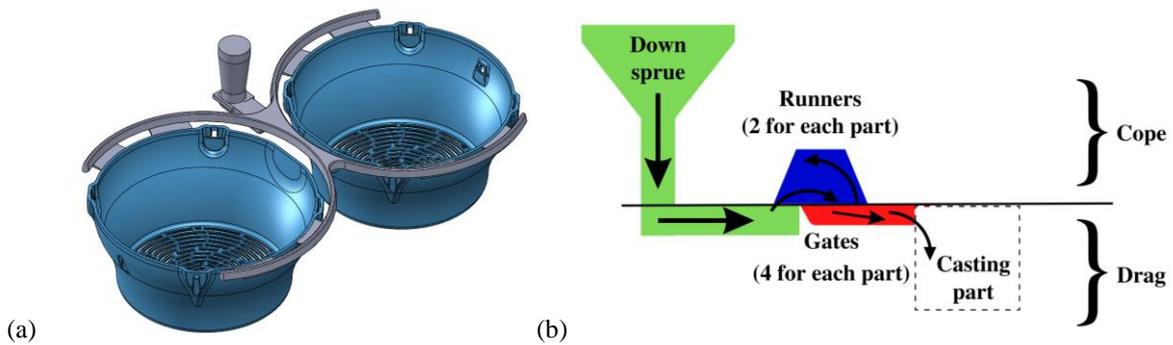


Figure 6. Filling and feeding system Design I (a) 3D; (b) schematic drawing.

Temperature analysis for Design I demonstrated reduced temperature loss. With the liquid metal reaching the fan cover grids between 1268 and 1287 °C (Figure 7(a)), that is a loss of around 150 °C about the pouring temperature (50 °C less than in the original design).

Analysis of Design I filling velocities demonstrated a turbulent filling mode, as is expected for a “waterfall” style filling and feeding system, which is evidenced by the high filling velocities in the region of the gates and the first region of liquid metal impingement gushed into the cavity of the part, and by the undulations of the metal as it fills the casting part cavity (Figure 7(b)). The turbulent filling can cause metal temperature loss as it maintains more contact with the air and can lead to the appearance of inclusions due to sand erosion and metallic spatter that solidify before the rest of the liquid metal and that is involved by an oxide layer.

In addition, it was observed that the runners' ends work empty for a long time, causing the last gates to take more time to receive liquid metal, which can lead to metal reoxidation, causing inclusions (oxides). This occurs because the runners

positioning in the cope and the gates in the drag (as previously illustrated in the schematic in Figure 6(b)) causes the liquid metal to reach the gates closest to the down sprue before filling the ends of the runners, so the metal reaches the casting part cavity before filling the entire feed system, which not only can cause inclusions but also intensifies the turbulent flow of the metal.

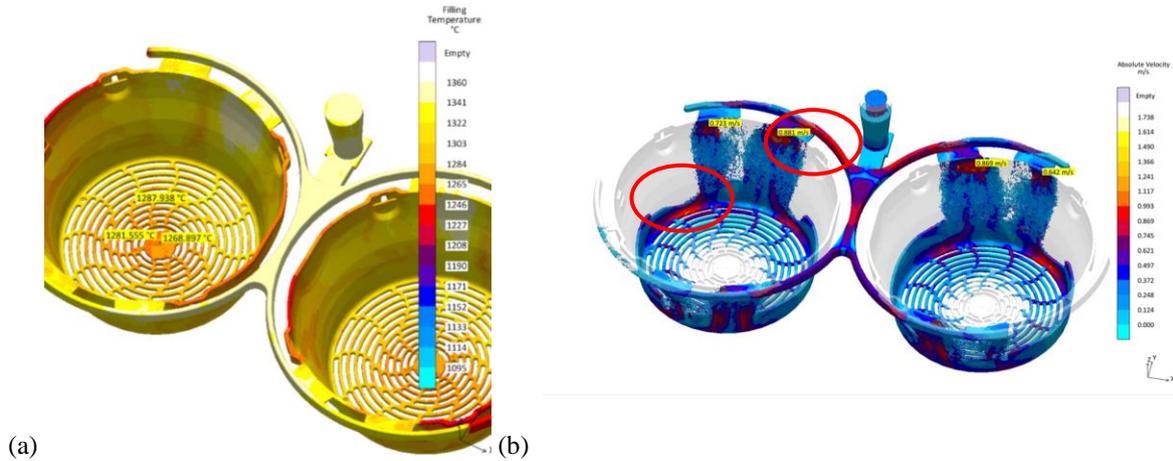


Figure 7. Filling and feeding system analysis of Design I: (a) temperature; (b) velocity.

4.2 Design II

Design II was also elaborated with 8 gates per piece, as in the original design, but keeping the same inverted filling direction as in Design I, but changing the position of the runners to be in the drag as well the gates. No other changes were made to the rest of the filling and feed system, keeping it depressurized about to the areas of runners and gates. Figure 8(a) and (b) show the 3D modeling of Design II and a schematic of the mold parting line and the path taken by the liquid metal during feeding, respectively.

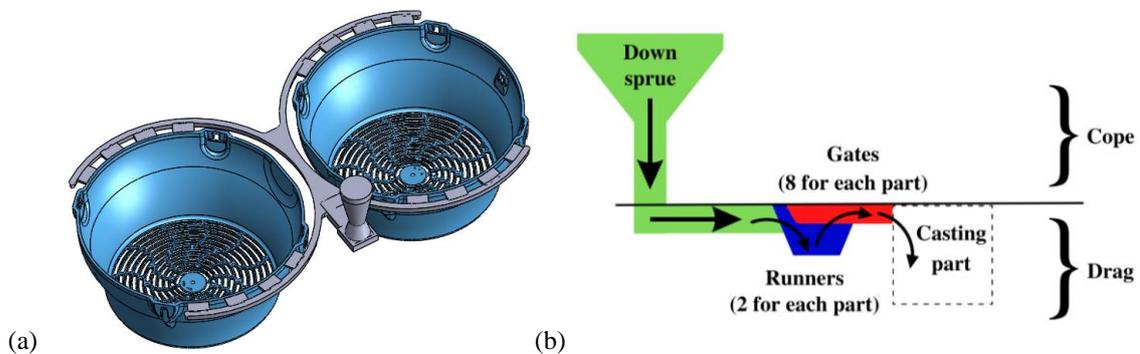


Figure 8. Filling and feeding system Design II (a) 3D; (b) schematic drawing.

The filling temperature analysis of Design II demonstrated that the filling and feeding system in the “waterfall” style decreases the metal temperature loss when filling the mold, maintaining still high temperatures when reaching the grid region (Figure 9(a)).

In the filling velocities analysis in Design II, it was possible to observe that changing the runners' position from the cope to the drag prevents the runners and gates from working empty, as in Design I. This is because this position allows the liquid metal hits all ends of the runners before reaching the gates, causing all the runners to feed into the casting part cavity withal (Figure 9(b)).

However, in a closer cut (Figure 9(c)), a preferential trajectory was observed in the liquid metal flow, forming a curvature in the region of the gates, which makes them work empty for a moment and favors the erosion of the mold, due to the impact on the runners and gates' corners.

In addition, when referring to Figure 9(d), it was noticed that the liquid metal still suffers strong turbulence in its inflow into the mold cavity, which again causes the defects seen in the test pieces of Design I.

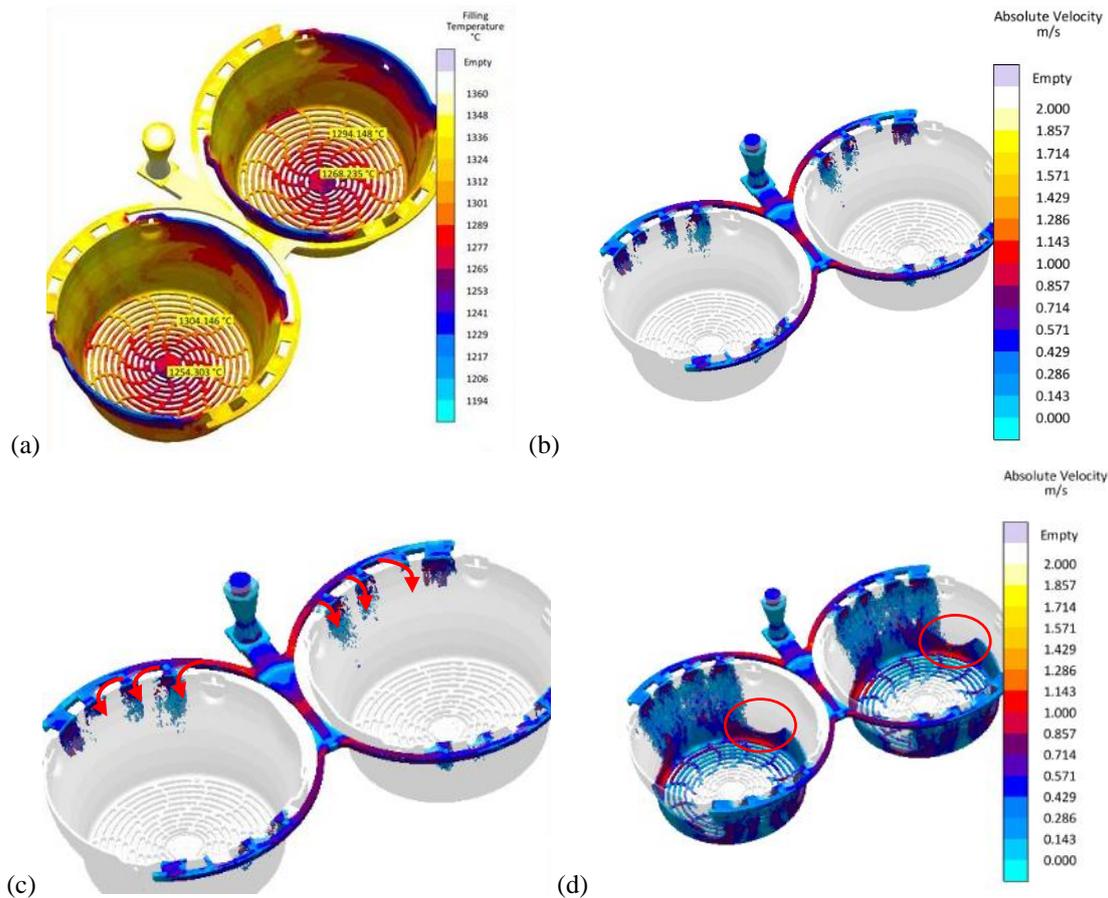


Figure 9. Filling and feeding system analysis Design II of (a) temperature; (b), (c) and (d) velocity.

4.3 Design III

Design III was created considering all the lessons learned from previous Designs. Again, the number of attack channels was reduced (2 per casting part) to have only one with a larger area at each end of the runners (but maintaining the system depressurized), which also facilitates the filling and feeding system removal after demolding because there are fewer gates connecting the casting part to the system.

The runners' and gates' position were maintained in the drag, and were assigned to the gates the curvature of the liquid metal preferential trajectory when entering the cavity of the casting part, as verified in the results of Design II.

The Design III filling and feeding system is shown in Figure 10(a), and Figure 10(b) is a schematic illustrating the mold parting line and liquid metal path during the Design III feed.

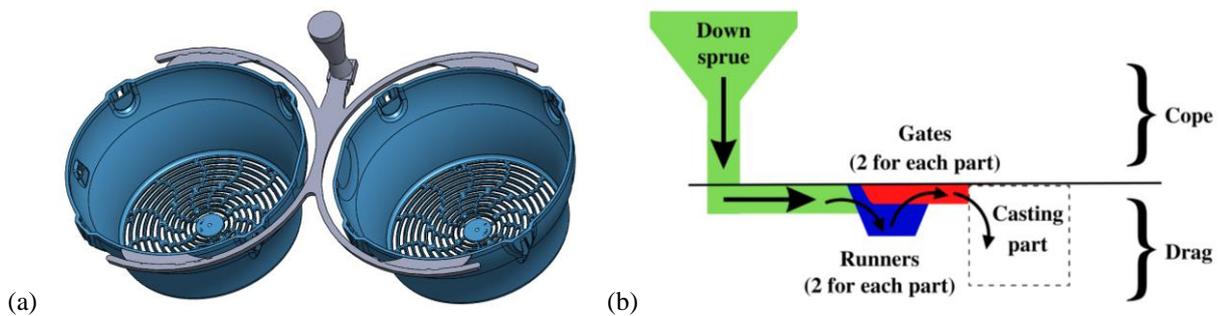


Figure 10. Filling and feeding system Design III (a) 3D; (b) schematic drawing.

In the temperature analysis of Design III, there was even less temperature loss between the moment that the liquid metal passes through the gates and the moment that it hits the fan cover grids in the mold cavity, as previously seen for

the other proposals for the filling and feeding system in “waterfall” style. The lowest temperatures occur at the edges of the part (last filling region), reaching approximately 1240 °C, enough to avoid the appearance of cold shut and misruns defects (Figure 11 (a)).

The filling velocities analysis of Design III showed what was already expected from the previous results. It was possible to verify a turbulence reduction of the metal when reaching the bottom of the mold cavity because, with the geometry change of the gates, the liquid metal did not suffer shocks when entering the mold cavity. In addition, the absence of shocks prevented sand from being carried to the mold cavity due to mold erosion. No section of the feed system was observed working empty because the runners are filled before the metal reaches the gates, which decreases the reoxidation tendency (Figure 11 (b)).

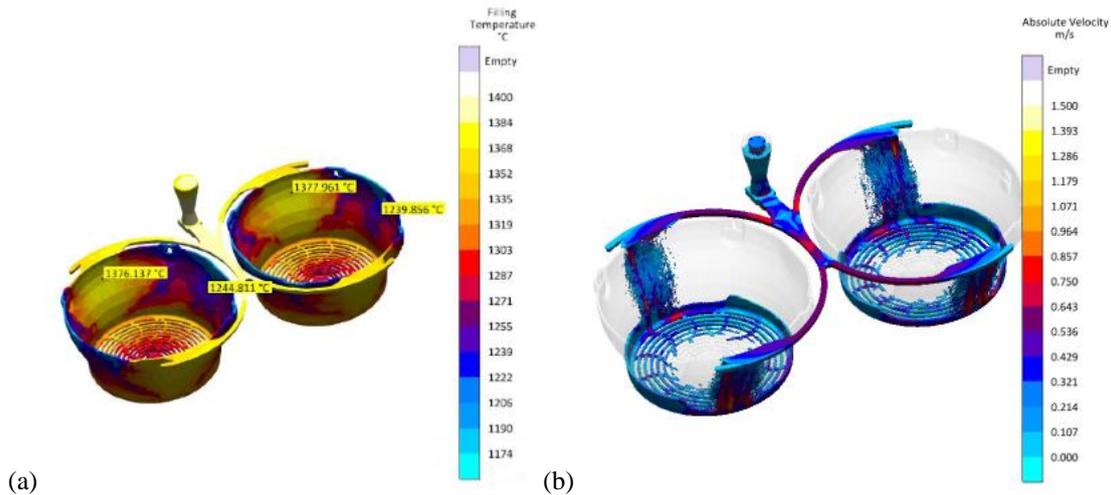


Figure 11. Filling and feeding system analysis Design III of: (a) temperature; (b), (c) and (d) velocity.

With the satisfactory results of Design III, practical tests were carried out with the pattern equipment filling and feeding system change. No cold shuts or misruns defects were verified, validating the filling temperature analysis results for the “waterfall” style systems (Figure 12(a)).

In addition, the casting part surface also did not show the defects mentioned in previous versions and the original model. As can be seen in Figure 12(b), the shot-blasted surface of the casting part has a clean and uniform appearance. The problem of sand consolidation, which causes erosion in regions close to the holes for inserting screws, was also eliminated.

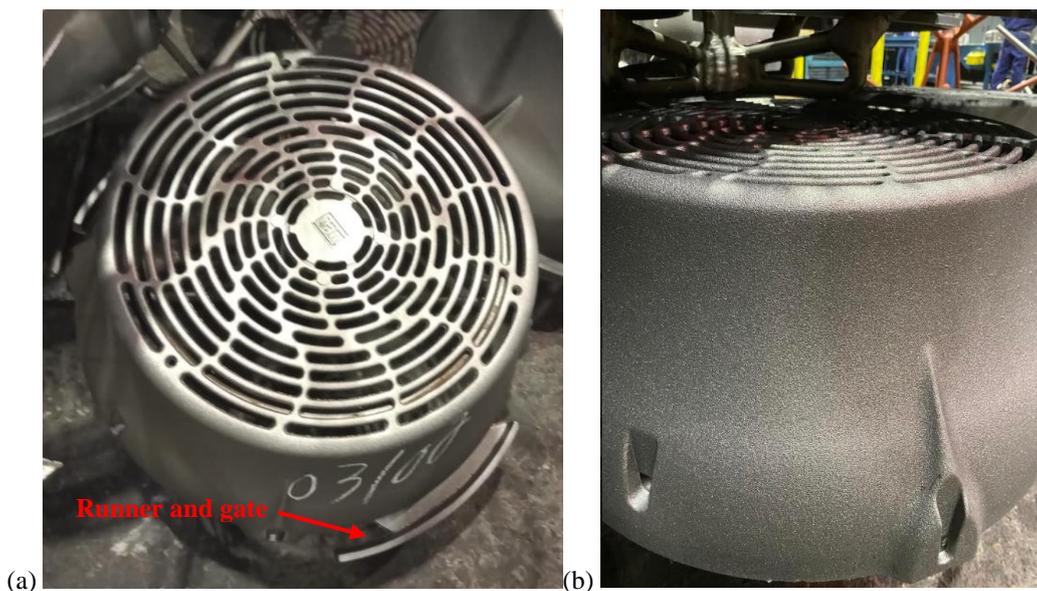


Figure 12. (a) Absence of cold shut and misruns defects; (b) Absence of sand erosion, burnt-on sand, and metallic penetration defects.

5. CONCLUSIONS

In this work, the redesign of the filling and feeding system of a mold to manufacture the motor fan cover in gray cast iron FC-200 was carried out. The objective of the redesign was to avoid defects such as cold shut and misruns, inclusions, burnt-on sand, and sand erosion. Three designs were developed considering the velocity and temperature distributions obtained by analysis of the filling using a numerical simulation software. From the investigation carried out in this work, the following conclusions can be drawn:

(a) The causes of cold shut and misruns defects in the original design were the liquid metal loss of pressure and temperature during mold filling.

(b) The difference of more than 200 °C between the inlet temperature of the metal and the temperature at which it reached the grids of the casting parts favored the early solidification of the metal, generating low diffusion between the filling fronts and misruns.

(c) The geometry and positioning of the gates about the casting part meant that the mold had a low consolidation of sand in some regions, which suffered erosion with the passage of liquid metal, causing defects of sand inclusions, burnt-on sand, and metallic penetration.

(d) It was possible to propose and improve designs to solve the defects mentioned from the temperatures and velocities of filling analysis with the MAGMA software.

(e) The inversion of the filling and feeding system and the mold cavities for the "waterfall" style eliminated the cold shut and misruns defects by making the liquid metal reach the grid region more quickly, losing less temperature.

(f) The tendency to inclusions and marks on the surface due to mold erosion of the "waterfall" filling and feeding system design was eliminated and avoided by understanding the preferential trajectory of the metal flow and the curve design of the gates in Design III, avoiding collisions in the mold corners, consequently, avoiding sand erosion.

(g) Design III of the gates also allowed a less turbulent flow inlet, avoiding reoxidation and spatter in the cavity of the casting part. These analyses were confirmed with practical tests of parts manufactured with Design III filling and feeding system in the pattern equipment, which presented clean casting parts without inclusions and with a uniform surface.

Up to the present it has not been possible to estimate the reduction in defects and to account for cost savings for the foundry company in which this study was conducted, as this requires large-scale testing. However, none of the 40 test parts manufactured with Design III showed cold shut and misruns defects. In addition, the time required for deburring the parts was reduced, causing an improvement in the casting parts finishing. With the analysis of the filling temperatures of Design III, it was verified that it is possible to reduce the pouring temperature down to 1380 °C, which is relevant since the heating of liquid metal is one of the biggest consumers of electricity in foundry companies.

6. ACKNOWLEDGEMENTS

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