Analysis of Cooling Conditions of A356 Aluminum Alloy Rim
Low-pressure Casting

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Abstract. At present, rims on the market are mostly made by aluminum alloy high-pressure casting. If the waiting and cooling time parameters of the air pipe are not controlled properly in the casting process, internal shrinkage of the rim often occurs after solidification. This study uses computer-aided analysis software MAGMASOFT to control the waiting and cooling time of the air pipe. The aluminum alloy rim casting process is simulated under different parameter conditions, according to the analysis result of steady-state convergence, the shrinkage index (SI) from the liquid entrapped phenomenon is used to observe the effect of the temperature difference between the rib midsection and rib tail section on rim casting shrinkage size, in order to improve shrinkage. The simulation program and SI may be used to predict rim casting quality in the future, determine the optimum process parameters, upgrade rim casting quality, and reduce rim production costs. Finally, the Taguchi method is used to obtain the optimum process parameter combination, with the intention of obtaining the best product stabilizing effect.

Introduction

The rim has evolved over three to four thousand years, from the earliest stone and wood products to modern cast iron rims, as well as to the more esthetic and lightweight aluminum alloy rim. The continuous evolution of the automotive rim not only improves the quality of human life, but also enhances living convenience. Over a decade ago, most vehicles were equipped with an iron ring with a plastic decorative cover sheet. The aluminum alloy rim was a deluxe product at that time, only belonging to deluxe vehicles, while general home-made vehicles could never have such high class standard equipment. In recent years, with technological advances, cost reductions, and consumer demands, various plants rank the aluminum alloy rim as standard equipment for most vehicles [1].

Recently, consumers' requirements for vehicle outfitting and quality grow increasingly, and consumers doubt the opinion that the brand and price are proportional to performance, thus, they pay attention to individualization and uniqueness. Therefore, some owners must change their vehicles to some extent, from full-vehicle surrounding, changing rims, and even to making the protecting cover into a little devil icon, thus, the trend and manifestation of personalization are more apparent. However, whatever the changes are, average consumers mostly equip their vehicles with aluminum alloy rims to express personal independence. According to the research investigation report of the ITIS program of the Department of Industrial Technology, Ministry of Economic Affairs [2], Europe, north America, and Japan strictly specify waste gas and waste reduction and recovery ratio, which are about to be forcibly implemented. Thus, aluminum products with light weight and good recoverability have become the best substitute for steel and plastic. Approximately 20% of global CO₂ emissions are from vehicle exhaust. In recent years, various countries legislated in succession to restrict automobile CO₂ emissions. The EU planned to reduce automobile CO₂ emissions by 45 % between 2003 and 2015, automobile suppliers must recover used cars unconditionally since 2007, and 80% of automobile parts must be recycled since 2006, and this
ratio was increased to 85% in 2015. The ITIS research report indicates that, as aluminum products can reduce CO$_2$ emissions, if vehicles use a ton of aluminum ingot, the CO$_2$ emission is reduced by 20 MT before the vehicle is rejected. The new environmental laws of Europe, north America, and Japan are intended to accelerate the use of aluminum products.

**Literature Review**

Feng et al. [3] took the A356 aluminum alloy rim cast in actual production as an example, used 3D drawing software for the 3D contouring of the solid model of the cast, used Z-CAST software for numerical simulation of the low-pressure casting filling and solidification processes of initial technique, predicted the type, position, and size of initial technique defects, and analyzed the causes. The results showed that, the initial technique resulted in casting defects of air entrapment and shrinkage as the pouring temperature was too low. The technique was optimized according to the simulation results, the pouring temperature was increased to 730°C, the casting process was simulated again, the defects were detected, and the quality of the cast was improved.

Kuo et al. [4] developed an interactive simulation system to improve the pressurization conditions of the low-pressure casting rim filling process. The general velocity field was known, and the calculation of tracking air particle was added in the program. The interactive simulation system judged the air particle entrapped in a time step. If the air particle was severely entrapped, the system automatically terminated the program, and a new inlet velocity condition was conducted in this time step to continue calculation till the optimum pressurization condition of the filling process was obtained.

Bao [5] used a 3D contouring technique for the solid modeling of a rim entity, used Any casting software for mesh division, and determined the initial conditions and boundary conditions. A check experiment was designed, numerical simulation was implemented, and the effect of mold temperature, melt temperature, and the time pressure curve on the filling time, filling sequence, filling stationarity, and air entrapment were studied. The results showed that, the mold temperature and melt temperature had slight effect on filling time, filling sequence, filling stationarity, and air entrapment, and the main influencing factor was the time pressure curve.

Yu et al. [6] adopted ProCAST to simulate the filling and solidification processes of an actual low-pressure casting magnesium alloy rim, analyzed the flow field and solid fraction field of molten magnesium in the model, provided the criteria of correcting the cooling system and filling condition, in order to eliminate shrinkage and gas hole defects.

Yu [7] employed the ProCAST software package to simulate the solidification process of a gravity casting rim, predicted the probable position of a sinkhole, and improved the riser design and model design.

Wang et al. [8] used the PAM-CAST software package to simulate the filling and solidification processes of the low-pressure casting magnesium alloy rim, analyzed the solid fraction field and velocity field of molten magnesium in the model in order to predict the probable sinkhole and gas hole positions, designed different cooling systems and filling rates, and observed the results, in order to provide an optimal design proposal.

Huang [9] utilized mold flow analysis software MAGMASOFT as the analytical tool, and discussed the flow distribution of molten metal and aluminum alloy solidification in different runner systems and cooling systems. The research discussed four different designs, the flow analysis of the rim and engine cylinder cap in different runner systems, and the effect of change in the overflow chamber design of the rim. The simulation results showed that low air pressure enabled the melt to flow smoothly. Finally, the effects of different cooling systems on the mold and rim were discussed, and the defects in the rim could be reduced by using an appropriate cooling system that matches the simulation results.

Singh et al. [10] used the ProCAST software package to fit the model temperature of an actual case of low-pressure casting, obtained the required heat transfer coefficient, and predicted the temperature and shrinkage position consistent with the actual case.
Zhang et al. [11] used the ABAQUS software package to simulate the temperature field and solid fraction field of an actual low-pressure casting rim case, embedded thermocouples in specific positions of the model and rim to measure the temperature, fit the model temperature after 10 thermal cycles of this case, and obtained the heat transfer coefficient for boundary conditions. Under strict process consideration and the effect of the aluminum pad on mold temperature when filling was abandoned, and the temperature and shrinkage defect position consistent with actual case were obtained.

Wen et al. [12] experimentally measured the temperatures in 20 positions of the model of a low-pressure casting aluminum alloy rim, and described the temperature trend of the model during the thermal cycle. The thermal cycle of low-pressure casting aluminum alloy rim contained a filling phase, solidification phase, mold unloading phase, and clamping phase. The model temperature varied with the aluminum pad, cooling channel, and environments in the cycle, with the intention to provide suppliers with reference for adjusting process parameters.

Chu [13] used the advantages of computer-aided analysis to discuss the effect of compression rate and environmentally natural cooling on the filling and solidification processes of the low-pressure casting aluminum alloy rim, analyzed air entrapment and solidification, proposed improved pressurization conditions, air forced convective cooling position, duration, mold release thickness, and model geometry correction, in order to reduce gas hole and shrinkage defects.

Achim Schrotth [14] designed the mold shape and cast, and found the positions that were vulnerable or might have defects with the assistance of CAE simulation, which were remedied by the new design. The process, mold plans, and product were completed almost simultaneously. The heat balance and temperature control are important standards in mold design, as such standards can reduce defects, and each casting cycle can be accelerated by controlling the mold temperature, in order to reduce the cost of compression casting.

Aluminum Alloy Rim Material

A356 aluminum alloy ingot is an AL-Si-Mg alloy, containing Si 6.5%~7.5% and Mg 0.2%~0.4%. It is a silver and glossy metal, the specific gravity is about 2.7, and the melting point is 660°C. It has good casting property, as well as light mass and heat sinking effect, which saves oil consumption and prolongs tire life, thus, it is the material universally used by aluminum rim plants [19]. Its thermophysical properties are as shown in Table 1.

| Name of working fluid | Heat transfer coefficient [k(W/m/K)] | Specific heat capacity | Latent heat | Density | Viscosity |
|-----------------------|-------------------------------------|------------------------|------------|---------|-----------|
|                       | $C_p^1(J/kgK)$ | $C_p^2(J/kgK)$ | $C_l^o(J/kgK)$ | Temperature range (K) | $\rho(kg/m^3)$ | $\mu(kg/m)/s$ |
| A356                  | 400 | 1190 | 1127 | 886.2>T>883.7 | 51020 | 2369 | 0.0013 (Zhu, 2006) |
|                       | 883.7>T>861.2 | 91200 | | 48740 | 2369 | 0.0013 (Zhu, 2006) |
|                       | 861.2>T>840.2 | 48740 | | 2369 | 0.0013 (Zhu, 2006) |

Description of low-pressure casting aluminum alloy rim production flow

The mold is preheated and sprayed with a mold coating agent, preheated in an oven chamber to 400°C, the mold is fixed to the low-pressure diecasting machine, the aluminum pad is prepressed from the crucible to fill the mold cavity, and a pressure lower than 1 kgf/cm² is applied to continuously supplement the aluminum pad. When the aluminum pad is solidified, the mold is opened, the cast is removed by a firing pin, and carried away by the receiving mechanism. The next casting cycle is entered when the mold is closed.
Research Purposes
The MAGMASOFT mold flow software is used for simulation, and the waiting and cooling time of the air pipe is controlled in order to know the temperature difference between the rib midsection and rib tail section when the solid fraction is 0.7, i.e. the aluminum pad supplementation is finished under different conditions to determine which condition has greater effect on the temperature difference, thus, foundry engineers have reference for setting conditional parameters, the cooling system can be reasonably controlled, and the thermal center is eliminated. The combination of optimum process parameter control factor levels is determined without disordering the progressive solidification. The effect of cooling conditions on the process is minimized to enhance the stability of the process, thus, guaranteeing continuous production and reducing defects.

Mold Flow Theory Analysis
The mold flow analysis of compression casting is based on fluid mechanics, the solidification theory, heat transfer, and applied mechanics. Some physical phenomena in the compression casting process are analyzed by numerical analysis, in order to determine the flow behavior and solidification process of molten metal in the compression mold cavity, mold heat transfer, and cast stress-strain, as well as to predict whether the mold design scheme will result in casting defects, such as gas hole, slag inclusion, shrinkage, and thermal deformation, as based on which mold scheme can be improved.

Brief Introduction to Business Software MAGMASOFT
MAGMASOFT is developed by Germany’s MAGMA Ltd for users to research casting and analyze the flow, heat transfer, and solidification stress. This paper uses Version 4.4. Germany’s MAGMA Ltd was founded in 1988, and its casting CAE software MAGMASOFT has over 800 users around the world. It has been used by 100 large-scale enterprises since April 2000, and affirmed by major European and north American foundries and auto plants. European and north American foundry and automobile industries have invested many resources into casting mold CAE simulation techniques in order to upgrade the quality of products. MAGMA is recognized as the worldwide leading manufacturer in the casting CAE domain; the major European, north American, and Asian auto plants, such as Ford, Volkswagen, BMW, AUDI, GM, Hyundai, TOYOTA, and Daewoo, while Chinese Mainland auto plants use MAGMASOFT software for CAE simulation of automobile parts casting process. In other castings industries, MAGMASOFT software is the main CAE simulation tool, the casting non-defective rate is higher than 95 %. In the last three years, Chinese Mainland and Korea imported and actively used casting CAE software to enhance the reliability of cast and casting techniques. Therefore, the predicted future growth of casting CAE software in Asia has been very apparent.

Introduction to Taguchi Method
The Taguchi method (TM) is a Design of Experiment, as developed by Japanese Dr. Genichi Taguchi in the 1960s, who combined the analysis of variance, as created by British statistician R.A. Fisher in agricultural experiments, which used the orthogonal array for planning the experiments of Indian scholar Rao, called the Taguchi experimental design method. The Taguchi method is derived from the traditional Fractional Factorial Design method, and improved by Genichi Taguchi, also known as Robust design. A robust means the sensitivity of the designed product quality to its surrounding is minimized, and the main spirit of the Taguchi method is to rapidly obtain the optimal experimental combination with fewer experiments (compared with full factorial experiment), in order to obtain useful statistical information. Although, theoretically, there will be accuracy loss (bias cannot be eliminated completely in general), in terms of the purpose for solving engineering quality problems, the Taguchi method is sufficient. The Taguchi Method uses the planned experimental orthogonal array and the S/N ratio, as derived from experimental data. The major
characteristic of the orthogonal array is that we can combine different experiments, the flexibility is high, and the number of experiments can be greatly reduced. The S/N ratio enables the experimenter to analyze data and easily determine the optimum combination of the factors influencing product quality. This study uses the Taguchi method to reduce the number of experiments, to render the experimental results accurate and efficient, aims at the design parameter combination for minimum variation of the product and robust design of the optimum product function, and aims to determine the major factors influencing the temperature difference between the rib midsection and the rib tail section.

**Experimental Method**

This paper uses the control of waiting and cooling times of 3 cooling air pipes as a variable, where the waiting and cooling time of air pipes are set as factors, and there are 6 factors. Each factor has 2 levels, as shown in Table 2. In the casting process, the solidification direction of cast is expected to be opposite to the aluminum pad supplement direction, thus, the shrinkage resulted from the solidifying part can be supplemented. However, the rib tail section is relatively thick and is likely to generate a thermal center, thus, in order to create a temperature field of directional solidification from the tire rim to the gate, the temperature difference between the rib midsection and rib tail section is controlled by changing the waiting and cooling times of the cooling air pipes, and because the aluminum pad can be continuously supplemented, shrinkage is reduced.

| Table 2. Factor level. |
|------------------------|
| **Factor** | Rib midsection air pipe | Lower mold PCD air pipe | Upper mold PCD air pipe |
| **Level** | Waiting time (s) | Cooling time (s) | Waiting time (s) | Cooling time (s) | Waiting time (s) | Cooling time (s) |
| Level 1 | 80 | 80 | 150 | 150 | 120 | 120 |
| Level 2 | 150 | 150 | 250 | 250 | 180 | 180 |

Description of shrinkage index

When the solid fraction is 0.7, the aluminum pad flow ability declines, and because the solidified aluminum pad cannot be supplemented by the external aluminum pad, the expansion and contraction of the aluminum pad, as resulted from solidification, will damage the casting quality, resulting in shrinkage [22]. The shrinkage index is the temperature difference between the rib midsection and rib tail section. When the temperature difference is small, the directional solidification from tire rim to disk can be created, and there will not be large shrinkage due to insufficient aluminum pad supplement.

**Introduction to Casting Simulation Process**

**Mold Scheme Design**

The design of a low pressure mold is as shown in Figure 1, which considers the solidification directionality of the mold, as well as the relationship between the mold and cast thickness, where the aluminum pad is cast in the center (center hole), and the aluminum pad flows from the center hole to the tire rim, in order to control the mold and cast thickness to guide solidification from the tire rim to the center hole. The rim shape usually has complex geometry, and the air is often used for cooling in order to implement directional solidification.
Casting Simulation Preprocessing

A complete 3D mold is built using CATIA; the model with an upper mold, lower mold, side mold, and gate runner system is as shown in Figure 2. The geometric model is loaded into MAGMASOFT to specify the cast and mold material attributes. The thermophysical properties of the mold model are as shown in Table 3.

Table 3. Thermophysical properties of model (Zhang, 2007).

| Model name                        | Heat transfer coefficient | Specific heat capacity | Density ρ(kg/m³) |
|----------------------------------|--------------------------|------------------------|------------------|
| Upper mold, lower mold, lift tube (H13) | 27.3                     | 650                    | 7369             |
| Side mold (cast iron)            | 39                       | 726                    | 7300             |

MAGMASOFT software uses the finite difference method to divide the mesh, and because the adopted mesh is a simple cuboid, the time for mesh division is relatively short. However, for a complex curved surface, there must be a large number of grids in order to present the shape of the curved surface. In order to display complex geometry, the cast mesh is divided into 300 cells, as shown in Figure 3.
Figure 3. Finite difference grid of cast.

Table 4. Boundary condition settings in various phases of the model with air forced convective cooling in thermal cycle (Zhang et al. 2007).

| Boundary type                              | Process time (s) | Environmental temperature (K) | * Heat transfer coefficient (W/m²K) |
|-------------------------------------------|------------------|-------------------------------|-------------------------------------|
| Between inner wall of upper mold and      | 0<t<12           | -                             | 0                                   |
| aluminum pad                              | 12<t<360         | -                             | 2000                                |
| Between inner wall of upper mold and      | *360<t<385       | *498                          | 600                                 |
| ambient air                               | *385<t<420       | *498                          | 10                                  |
| Between inner wall of lower mold and      | 0<t<12           | -                             | 0                                   |
| aluminum pad                              | 12<t<360         | -                             | 2500                                |
| Between inner wall of lower mold and      | *360<t<385       | *498                          | 10                                  |
| ambient air                               | *385<t<420       | *498                          | 10                                  |
| Between inner wall of side mold and       | 0<t<12           | -                             | 0                                   |
| aluminum pad                              | 12<t<360         | -                             | 2000                                |
| Between inner wall of side mold and       | *360<t<385       | *498                          | 10                                  |
| ambient air                               | *385<t<420       | *498                          | 10                                  |
| Between outer wall of upper mold, lower   | 0<t<420          | *498                          | 20                                  |
| mold, side mold and environment           |                  |                               |                                     |
| Between lift tube and aluminum pad        | 0<t<420          | -                             | 0                                   |
| Between lift tube and environment         | 0<t<420          | *973                          | 0                                   |

Boundary condition settings: the material properties, initial values, and boundary conditions are given according to the actual state. For example, the initial temperature is set as 400°C, and the pouring temperature of the aluminum pad is set as 700°C. The boundary conditions in various phases when the model is in the thermal cycle are as shown in Table 4. Table 5. shows the maximum relative error between the initial temperatures of the model in each thermal cycle. In the case of air forced cooling, the model temperature is stabilized after 5 thermal cycles, thus, the result of the 5th simulation is taken as the object. The casting plan sets air pipe waiting and cooling times according to 6 factors, which are the probable significant factors, and each factor has 2 levels, thus, the L16 (2⁶) orthogonal array is selected. There are 16 experimental plans, as shown in Table 6.

Table 5. Maximum relative error between the initial temperatures of the model in each thermal cycle (with air forced convective cooling).

|                           | 1st vs. 2nd | 2nd vs. 3rd | 3rd vs. 4th | 4th vs. 5th |
|---------------------------|-------------|-------------|-------------|-------------|
| Maximum relative error    | 4.6%        | 2.4%        | 1.4%        | 0.9%        |
The numerical computation is implemented according to the imported mold parameters, initial values and boundary conditions, the temperature, velocity and flow results are obtained.

**Experimental Results and Analysis**

The experiment is conducted according to the experimental combination, the temperature difference between the rib midsection and rib tail section when the solid fraction is 0.7 is recorded, and MINITAB statistical software is used to calculate the S/N ratio, as shown in Table 7. The temperature difference between the rib midsection and rib tail section is the smaller the better. According to the main effect plots of Figure 4. and Table 8, the S/N ratio difference is "lower mold PCD air pipe waiting time" > "upper mold PCD air pipe cooling time" > "rib midsection air pipe cooling time" > "lower mold PCD air pipe cooling time" > "upper mold PCD air pipe waiting time" > "rib midsection air pipe waiting time"; the factors "lower mold PCD air pipe waiting time" and "upper mold PCD air pipe cooling time", which have significant effect, while the other factors have no significant effect. Therefore, the optimum condition is "A1B1C2D1E2F1", which condition is identical to the 4th experimental configuration.

**Table 6. Experimental plan.**

| Plan | Rib midsection air pipe | Lower mold PCD air pipe | Upper mold PCD air pipe |
|------|-------------------------|-------------------------|-------------------------|
|      | Waiting time (s) | Cooling time (s) | Waiting time (s) | Cooling time (s) | Waiting time (s) | Cooling time (s) |
| 1    | 80 | 80 | 250 | 150 | 180 | 180 |
| 2    | 150 | 150 | 250 | 250 | 180 | 180 |
| 3    | 80 | 80 | 150 | 150 | 120 | 120 |
| 4    | 80 | 80 | 250 | 150 | 180 | 120 |
| 5    | 80 | 150 | 150 | 150 | 180 | 180 |
| 6    | 150 | 150 | 250 | 150 | 180 | 120 |
| 7    | 150 | 150 | 150 | 150 | 120 | 180 |
| 8    | 80 | 80 | 150 | 250 | 120 | 180 |
| 9    | 150 | 80 | 250 | 150 | 120 | 180 |
| 10   | 150 | 150 | 150 | 250 | 120 | 120 |
| 11   | 80 | 150 | 150 | 250 | 120 | 120 |
| 12   | 80 | 150 | 250 | 150 | 180 | 120 |
| 13   | 80 | 150 | 150 | 150 | 180 | 120 |
| 14   | 150 | 80 | 250 | 150 | 120 | 180 |
| 15   | 150 | 80 | 250 | 150 | 180 | 120 |
| 16   | 150 | 80 | 250 | 150 | 180 | 120 |

The numerical computation is implemented according to the imported mold parameters, initial values and boundary conditions, the temperature, velocity and flow results are obtained.

**Table 7. Experimental results.**

| Plan | Rib midsection air pipe | Lower mold PCD air pipe | Upper mold PCD air pipe | Temperature difference (°C) | S/N ratio |
|------|-------------------------|-------------------------|-------------------------|----------------------------|-----------|
| 1    | 1 | 1 | 2 | 1 | 2 | 2 | 12.165 | -21.7022 |
| 2    | 2 | 2 | 2 | 2 | 2 | 2 | 12.554 | -21.9756 |
| 3    | 1 | 1 | 1 | 1 | 1 | 1 | 12.673 | -22.0576 |
| 4    | 1 | 1 | 2 | 1 | 2 | 1 | 11.657 | -21.3317 |
| 5    | 1 | 2 | 1 | 1 | 2 | 2 | 13.138 | -22.3706 |
| 6    | 2 | 2 | 2 | 1 | 2 | 1 | 12.017 | -21.5959 |
| 7    | 2 | 2 | 1 | 1 | 1 | 2 | 13.203 | -22.4135 |
| 8    | 1 | 1 | 1 | 2 | 1 | 2 | 13.336 | -22.5005 |
| 9    | 2 | 1 | 1 | 1 | 2 | 1 | 12.357 | -21.8235 |
| 10   | 2 | 1 | 1 | 1 | 1 | 2 | 13.357 | -22.5142 |
| 11   | 1 | 2 | 2 | 1 | 1 | 1 | 12.3 | -21.7981 |
| 12   | 1 | 2 | 2 | 1 | 1 | 1 | 12.772 | -22.1252 |
| 13   | 1 | 2 | 1 | 2 | 2 | 1 | 13.076 | -22.3295 |
| 14   | 2 | 1 | 2 | 2 | 1 | 1 | 11.831 | -21.4604 |
| 15   | 2 | 1 | 2 | 2 | 2 | 1 | 13.41 | -22.5486 |
| 16   | 2 | 1 | 1 | 2 | 1 | 2 | 12.405 | -21.8719 |
Table 8. Temperature difference s/n.

| Level | Waiting time of the rib midsection air pipe (A) | Cooling time of the rib midsection air pipe (B) | Waiting time of the lower mold PCD air pipe (C) | Cooling time of the lower mold PCD air pipe (D) | Waiting time of the upper mold PCD air pipe (E) | Cooling time of the upper mold PCD air pipe (F) |
|-------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1     | -22.03                                        | -21.91                                        | -22.33                                        | -21.95                                        | -22.09                                        | -21.87                                        |
| 2     | -22.03                                        | -22.14                                        | -21.73                                        | -22.1                                         | -21.97                                        | -22.18                                        |
| Delta | 0                                             | 0.23                                          | 0.6                                           | 0.14                                          | 0.12                                          | 0.31                                          |
| Rank  | 6                                             | 3                                             | 1                                             | 4                                             | 5                                             | 2                                             |

The optimum condition is imported into the minitab statistical analysis software in order to predict the S/N ratio of the optimum factor level combination, as shown in Table 4. According to the prediction values, the temperature difference is 11.62, and the S/N ratio is -21.3245. Regarding the 4th experimental combination, the temperature difference is 11.657, and the S/N ratio is -21.3317. Their gaps are very small, thus, the experimental results are reliable.

Figure 4. Temperature difference main effect plot.

Table 9. Conditional forecast.

| S/N Ratio | Mean   |
|-----------|--------|
| -21.3245  | 11.6202|

| Waiting time of the rib midsection air pipe (A1) | Cooling time of the rib midsection air pipe (B1) | Waiting time of the lower mold PCD air pipe (C2) | Cooling time of the lower mold PCD air pipe (D1) | Waiting time of the upper mold PCD air pipe (E2) | Cooling time of the upper mold PCD air pipe (F1) |
|-------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 80                                              | 80                                            | 250                                          | 150                                          | 180                                          | 120                                          |

The actual casting experiment is conducted according to the optimum parameter conditions. The experimental results are as shown in Figure 5, and there is no apparent visual shrinkage in the rib tail section.

Figure 5. Actual production section

Conclusion.
The following conclusions are obtained by analyzing the cooling conditions of A356 aluminum alloy rim low-pressure casting:

According to the experimental results, the factors of "lower mold PCD air pipe waiting time" and "upper mold PCD air pipe cooling time" have significant effect, and are the major factors that influence the temperature difference between the rib midsection and rib tail section. If the two factors are modified in the process, it is required to avoid shrinkage and dispersed shrinkage.

The 4th experimental combination - "A1B1C2D1E2F1" (rib midsection air pipe waiting time: 80 seconds, rib midsection air pipe cooling time: 80 seconds, lower mold PCD air pipe waiting time: 250 seconds, lower mold PCD air pipe cooling time: 150 seconds, upper mold PCD air pipe waiting time: 180 seconds, upper mold PCD air pipe cooling time: 120 seconds) are the optimum casting process parameters.

The actual casting is tested according to the optimum parameters, and there is no apparent visual shrinkage in the rib tail section.

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