Multi-objective optimization of process parameters during low-pressure die casting of AZ91D magnesium alloy wheel castings

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Abstract: Multi-objective optimization has been increasingly applied in engineering where optimal decisions need to be made in the presence of trade-offs between two or more objectives. Minimizing the volume of shrinkage porosity, while reducing the secondary dendritic arm spacing of a wheel casting during low-pressure die casting (LPDC) process, was taken as an example of such problem. A commercial simulation software ProCAST™ was applied to simulate the filling and solidification processes. Additionally, a program for integrating the optimization algorithm with numerical simulation was developed based on SiPESC. By setting pouring temperature and filling pressure as design variables, shrinkage porosity and secondary dendritic arm spacing as objective variables, the multi-objective optimization of minimum volume of shrinkage porosity and secondary dendritic arm spacing was achieved. The optimal combination of AZ91D wheel casting was: pouring temperature 689 °C and filling pressure 6.5 kPa. The predicted values decreased from 4.1% to 2.1% for shrinkage porosity, and 88.5 μm to 81.2 μm for the secondary dendritic arm spacing. The optimal results proved the feasibility of the developed program in multi-objective optimization.

Key words: magnesium alloy; multi-objective optimization; process parameters; shrinkage porosity; secondary dendritic arm spacing

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Wheels are widely used in automotive applications^[1]. To achieve excellent mechanical properties, low pressure die casting (LPDC) process is applied to manufacture wheels. Many studies have been carried out on the optimization of the LPDC process for magnesium wheels^[2-4]. Among these studies, it is common to use the traditional trial-and-error method. However, manual design, experiment and redesign take up too much time and yet may not obtain the optimal designs. To meet the requirements of high-efficiency and high-quality design, an automatic multi-objective optimization program based on SiPESC (i.e. Software Integration Platform for Engineering and Scientific Computation) was developed^[5]. Multi-objective optimization is concerned with problems involving more than two objectives to be optimized simultaneously^[6]. With SiPESC as the

support platform, it can achieve automatic updates of process parameters and numerical optimization during the whole LPDC process, facilitating the selection of optimal parameters combinations^[7]. ProCAST was used to simulate the LPDC process of an AZ91D magnesium alloy wheel casting. Numerical simulations were performed to investigate the effects of pouring temperature and filling pressure on shrinkage porosity and secondary dendritic arm spacing, and therefore to identify the optimal combination of process parameters during the LPDC process. Thus, the capabilities of an automatic multi-objective optimization program based on SiPESC were highlighted.

1 Steps of LPDC simulation

1.1 Geometric and finite element models

The wheel model with the height of 160 mm and diameter of 420 mm was designed by UG software, as shown in Fig. 1(a). The body had a regular outer shape and internal hollow structure, and the thinnest part of the wheel casting was 5 mm. The wheel model was meshed

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into 5 mm and the three-dimensional 4-node linear tetrahedral elements were adopted in the finite element model. The mesh generation results can be seen in Fig. 1(b), in which the element number was 167,494. The casting die was meshed into 10 mm, with 136,349 element number. The entire grid was exported to the ProCAST to perform LPDC simulation.

Fig. 1: (a) Geometry of wheel (b) Finite element mesh of wheel

1.2 Initial and boundary conditions

A typical AZ91D magnesium alloy with the composition given in Table 1 was studied. The initial and boundary conditions used in the present simulation are as follows: the density of the alloy at room temperature is $1,820 \text{ kg}\cdot\text{m}^{-3}$, the liquidus is 602°C , and the solidus is 422°C . The casting die is steel H13; its density is $7,625 \text{ kg}\cdot\text{m}^{-3}$. The thermal conductivity and the specific heat of the casting and die at different temperatures are in accordance with the commercial ProCAST database. To ensure the sequence solidification, the initial temperature of the side die, top die, and bottom die are 360°C , 380°C and 400°C , respectively.

Table 1: Chemical composition of AZ91D magnesium alloy (wt.%)

Al	Zn	Mn	Si	Cu	Ni	Fe	Mg
9.06	0.55	0.28	0.03	0.02	0.0035	0.004	Bal.

Various stages during the LPDC process include: AB-ascending stage, BC-filling stage, CD-boosting stage, DE-maintaining stage, and EF-releasing stage, as shown in Fig. 2. The initial pressure parameters were calculated according to the Handbook of Casting Forming [8].

Fig. 2: Typical pressure curve of LPDC process of AZ91D alloy

1.3 Determination of process parameters and objectives

Process parameters such as pouring temperature, filling pressure and pressure holding time, are crucial to casting quality. The first parameter to be decided is pouring temperature; its value range is established based on experiments. The reasonable range of pouring temperature for AZ91D is set from 680°C to 720°C [9, 10]. Another process parameter to be decided is filling pressure. Filling pressure is applied to push the molten metal into the die [11]. It can be calculated by Pascal's law, as shown in Eq. (1):

$$P = \frac{h\rho k}{10200} \quad (1)$$

where ρ is the density of the molten metal, k is constant 1.5, and h is the height difference between the surface of the melt and the top of the feeding tube, varying from 16 cm to 30 cm. The minimum filling pressure required to overcome the 16 cm metal pressure in the tube is calculated to be 4.3 kPa. The range of filling pressure is set between 4.3 kPa and 8.0 kPa. In casting design, there are two main objectives: eliminating casting defects and maximizing yield strength [12, 13]. In this study, pouring temperature and filling pressure are selected to be the design variables, the objectives are characterized by the volume of shrinkage porosity and secondary dendritic arm spacing in the region between the spoke and the rim.

2 LPDC simulation with SiPESC

2.1 Automatic optimization workflow

To begin, the finite element model of the wheel casting was exported from UG software, then the entity grid was imported into ProCAST. During the whole process, the input parameters were modified according to the specified optimization algorithm implemented on SiPESC. After each simulation on ProCAST, the value of the output parameter was read, then whether the objective was optimal or not was determined. If the objective was optimal, the optimization was completed. Otherwise, the input parameters were modified and reiterated until the ideal target value was achieved [14]. The workflow is shown in Fig. 3.

Fig. 3: Workflow of automatic optimization on SiPESC

2.2 Data exchange

Optimization of the process requires data exchange, which was realized through file transfer. The challenge was to run a sequence of simulations with multi-input parameters on the ProCAST backstage. The process parameters were written into an input file (preprocessing.py), then ProCAST software executed batch command (*.bat) to run the simulation. Finally,

the results were written into an output file (postprocessing.py). The JavaScript programming language was used to compile the program. Based on SiPESC, update script (Update.js) was used to obtain each new response value which would later lead to the change of input process parameters; optimize script (Optimize.js) was used to select the proper optimization algorithm regarding the specified problem. Through the entire iterative process, automatic multi-objective optimization was achieved. The framework of multi-objective optimization of the LPDC process is shown in Fig. 4. The result can be stored and obtained through free Sqliteman software.

2.3 Optimization algorithm

During the LPDC process, the filling speed is relatively slow, so the laminar flow model is used. The corresponding momentum and energy equations are given in Eq. (2)-(5):

$$\frac{\partial u}{\partial t} = g_x - \frac{1}{\rho} \cdot \frac{\partial p}{\partial x} - \left\{ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \omega \frac{\partial u}{\partial z} + r \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] \right\} \quad (2)$$

$$\frac{\partial v}{\partial t} = g_y - \frac{1}{\rho} \cdot \frac{\partial p}{\partial y} - \left\{ u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \omega \frac{\partial v}{\partial z} + r \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right] \right\} \quad (3)$$

$$\frac{\partial \omega}{\partial t} = g_z - \frac{1}{\rho} \cdot \frac{\partial p}{\partial z} - \left\{ u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} + \omega \frac{\partial \omega}{\partial z} + r \left[\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} + \frac{\partial^2 \omega}{\partial z^2} \right] \right\} \quad (4)$$

$$\rho_\varphi \left\{ u \frac{\partial y}{\partial x} + v \frac{\partial y}{\partial x} + \omega \frac{\partial y}{\partial x} + \frac{\delta y}{\delta x} \right\} = \frac{\partial}{\partial x} \left\{ \lambda \frac{\partial T}{\partial x} \right\} + \frac{\partial}{\partial y} \left\{ \lambda \frac{\partial T}{\partial y} \right\} + \frac{\partial}{\partial z} \left\{ \lambda \frac{\partial T}{\partial z} \right\} + \frac{\partial T}{\partial t} \quad (5)$$

where

u, v, w – velocity vectors, $\text{m} \cdot \text{s}^{-1}$;

x, y, z – coordinate component;

p – the pressure per unit density, Pa;

ν – viscosity, $\text{m}^2 \cdot \text{s}^{-1}$;

g_x, g_y, g_z – gravity component in each direction, $\text{m} \cdot \text{s}^{-2}$;

t – filling time, s;

T – temperature, $^\circ\text{C}$;

ρ – density, $\text{kg} \cdot \text{m}^{-3}$;

λ – thermal conductivity, $\text{W} \cdot (\text{m} \cdot \text{K})^{-1}$;

F – fluid volume, ml.

Ant colony optimization (ACO) algorithm was used as the optimization algorithm^[15, 16]. ACO is one of the search and global optimization methods that has the advantage of solving complex coupling problems. The process variables change automatically according to the following rules: (1) The start and end variables can only be calculated once; (2) The more intense the increments between two calculations, the greater the probability that it will be selected.

Since a shrinkage porosity-free casting is always desired, the porosity requirement was $\text{SP}(x) = 0\%$. The secondary dendritic arm spacing $\text{SDAS}(x)$ is not defined due to the unlimited value. The optimization problem was defined as follows: Minimize $f(x) = [\text{SP}(x), \text{SDAS}(x)]$, subject to $g(x) = [\text{SP}(x) = 0]$, where $x = [T, P]T, 680 \leq T \leq 720 \text{ } ^\circ\text{C}, 4.3 \text{ kPa} \leq P \leq 8.0 \text{ kPa}$. The focus was primarily on the automatic optimization where numerical simulation is employed to predict the values of the objective variables.

Fig. 4: Optimization of LPDC process parameters

3 Analyses of simulation results

In order to analyze the effects of process parameters on microstructure, a single factor method was used. Two different process parameters, pouring temperature and filling pressure, were simulated by controlling design variables.

3.1 Effect of pouring temperature on shrinkage porosity and microstructure

Using the initial and boundary conditions mentioned above, the calculations have been done for LPDC process. Figure 5 shows that when the filling pressure was 4.3 kPa, the iterative results change with the increasing pouring temperature. The profiles of volume of shrinkage porosity and secondary dendritic arm spacing under different pouring temperatures were not similar. The pouring temperature had a greater influence on the secondary dendritic arm spacing. With the pouring temperature increasing from 680 $^\circ\text{C}$ to 720 $^\circ\text{C}$, the secondary dendritic arm spacing increased from 87.5 μm to 93.7 μm .

When the pouring temperature was above 691 $^\circ\text{C}$, the tendency to shrinkage gradually increased with an increase in pouring temperature, while the microstructure was coarsened. When the pouring temperature was lower than 691 $^\circ\text{C}$, the liquid flow-ability was reduced, thus weakening the feeding capacity, increasing the tendency to shrinkage porosity, the phenomenon especially common in thin-wall pieces^[17]. Therefore, to facilitate the formation of the thin-walled components of magnesium alloy, the pouring temperature should be higher; whilst to reduce the tendency of shrinkage porosity, the pouring

Fig. 5: Effect of pouring temperature on shrinkage porosity and secondary dendritic arm spacing

temperature should be as low as possible. Under this condition, the optimal pouring temperature was 691°C.

3.2 Effect of filling pressure on shrinkage porosity and microstructure

When the pouring temperature was 691 °C, the change of objective variables with the filling pressure is shown in Fig. 6. It can be seen that with the filling pressure increasing from 4.3 kPa to 8.0 kPa, the secondary dendritic arm spacing decreased from 87.6 μm to 81.9 μm. The results, calculated with numerical simulation, showed a good correspondence with previous research^[18].

In the case where the pouring temperature is constant, the filling speed depends on the increasing rate of the gas pressure acting on the surface of the alloy. The higher the filling pressure, the faster the filling speed. When the filling pressure was above

Fig. 6: Effect of filling pressure on shrinkage porosity and secondary dendritic arm spacing

6.4 kPa, there will be shock splash in the cavity, resulting in porosity defects. Conversely, the lower the filling pressure, the slower the filling speed. When the filling pressure was lower than 6.4 kPa, the feeding capacity was restricted, which may also cause the shrinkage defects^[19].

3.3 Combinational optimization results

By setting pouring temperature and filling pressure as designed variables, the overall process during the filling and solidification stages of LPDC for an AZ91D wheel casting was numerically analyzed. The simulation results with optimized process parameters are shown in Table 2. The results show that the volume of shrinkage porosity after optimization can be improved from 4.1% to 2.1%, and the secondary dendritic arm spacing can be shortened from 88.5 μm to 81.2 μm.

Table 2: Combinational optimization of process parameters and corresponding predicted responses

Iteration	Pouring temperature (°C)	Filling pressure (kPa)	Shrinkage porosity (%)	Secondary dendritic arm spacing (μm)
1	680	4.3	4.1	87.5
2	689	6.5	2.1	81.2
3	703	6.8	2.7	86.7
4	712	7.4	3.5	85.6
5	720	8.0	3.9	88.5

The optimum combination result of process parameters was pouring temperature of 689 °C and filling pressure of 6.5 kPa. The whole filling process took approximately 6.2 s. At the beginning, the liquid metal flowed smoothly into the center of the wheel. At 1.7 s, the liquid metal reached the junctions between the rim and the spokes. At 2.8 s, the liquid alloy joined together at the bottom of the rim, then the liquid alloy rose steadily and arrived at half height of the rim at 4.3 s. At this moment, the temperature decreased to 640 °C and the alloy was still in fluid state. When the cavity was filled entirely, the temperature of the metal was above the liquidus 602 °C. During the whole filling process, no splashes or misrun occurred, as shown in Fig. 7.

The LPDC simulation ceased at 400 °C. When the cavity was filled with melted metal, the cavity was still in fluid state, and then it started to solidify. Figure 8 shows the distribution of solid fraction of the wheel casting during the solidification process of LPDC. The solidification started from the top of the rim to the bottom of the wheel, which ensured the sequence solidification during the whole process. The whole solidification process lasted around 401.5 s.

Another combination of process parameters was selected to compare with the optimal result. Figure 9 and Fig. 10 show the final distribution of shrinkage porosity and contour of secondary dendritic arm spacing in the casting with different process

Fig. 7: Temperature distribution during filling process of LPDC at pouring temperature of 689°C and filling pressure of 6.5 kPa

Fig. 8: Solid fraction during solidification process of LPDC at pouring temperature of 689°C and filling pressure of 6.5 kPa

Fig. 9: Comparison between results of shrinkage porosity before (a) and after optimization (b)

parameter combinations. It can be seen that shrinkage porosity mainly exists in the region between the rim and the spoke, which had the largest volume and remained liquid for a long period, whereas the other parts had moderate shrinkage porosity, as shown in Fig. 9. According to the theory of low-pressure die casting and production experience, the shrinkage of the casting is mainly caused by overheating. The thicker the part of the casting, the more likely the shrinkage porosity occurs. Because the change in wall thickness at the above location is relatively great, as the feeding channel of the casting is disconnected, the isolated liquid cannot be fed with the external liquid in time. The casting shrinks locally and causes local overheating of the casting, resulting in shrinkage porosity.

Moreover, the entire secondary dendritic arm spacing was

Fig. 10: Comparison between results of secondary dendritic arm spacing before (a) and after (b) optimization

refined by adopting the optimal process parameter, as can be seen in Fig. 10. With pouring temperature at 689 °C and filling pressure at 6.5 kPa, the volume of shrinkage porosity at the junctions was reduced to 2.1% and the secondary dendritic arm spacing was refined to 81.2 μm, thus the multi-objective optimization of LPDC process was achieved.

4 Conclusions

In this study, the proposed optimization program was developed to achieve multiple objectives automatically. Optimization of the LPDC process of AZ91D wheel casting was carried out on SiPESC using ACO algorithm. The program was designed to obtain an optimal combination between the shrinkage porosity and secondary dendritic arm spacing, which provided a reference for the selection of process parameters. The following conclusions can be drawn:

(1) Pouring temperature and filling pressure play major roles in LPDC process, both of which have greater influence on the secondary dendritic arm spacing than on the shrinkage porosity.

(2) With the optimal parameter combination, the predicted value for shrinkage porosity decreases from 4.1% to 2.1%, while the secondary dendritic arm spacing is refined from 88.5 μm to 81.2 μm. The optimal results prove the feasibility of the developed program in multi-objective optimization.

(3) Results of optimization provide a reference to LPDC process for selection of optimal parameter combinations. In this study, the optimum combination of LPDC process was: pouring temperature of 689 °C and filling pressure of 6.5 kPa.

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