Journal of the Chinese Society of Mechanical Engineers, Vol.47, No.1, pp59~74 (2026)

Research on Optimization of Injection Mould Process Parameters Based on The Upper Bracket of Automobile Front-End Frame

Zhendong Zhang*, Shanshan Peng*and Hu Wu

Key words: the upper bracket of automobile front-end frame, gating system, process parameters optimization, genetic algorithm

ABSTRACT

Aiming at the injection mould process parameter optimization methods are relatively few, and there is no combination of multiple multi-objective optimization methods to carry out optimization research. In this paper, the gating system of the upper bracket of automobile front-end frame is designed, and the flow channel system of the upper bracket of automobile front-end frame is simulated. The orthogonal experiment of the upper bracket of automobile front-end frame is designed. The multi-objective injection mould process parameters of the parts are optimized by the grey relational analysis (GRA) method, and the optimal process parameters and the influence degree of each factor on the evaluation index are obtained. The second-order response surface model of the evaluation index was established with the key influencing factors, and the multi-objective optimization of the model was carried out with the genetic algorithm, and the optimal injection mould process parameters of the parts were obtained. The upper bracket of automobile front-end frame optimized by the design was physically injected. The feasibility of the optimization method of injection mould process parameters was verified.

INTRODUCTION

In the process of injection mould, various defects often occur in the product due to the inaccurate setting of process parameters. When the material, structure and mold of the product have been determined, the defects in the injection mould process can be controlled by adjusting the process parameters. However, there are many process parameters that affect the quality of the injection mould product. At the same time, the degree of influence of different injection mould process parameters on product quality is also different. Therefore, in order to obtain accurate molding process parameters, it is necessary to use some optimization methods to optimize the molding process parameters.

Sun Shiren (2022) used the H12 shield as a research subject and employed Moldflow simulations to gather data on filling time, volumetric shrinkage, and related parameters. Moreover, he predicted possible injection mould defects, made corresponding analysis and optimization in accordance with these defects. At last, after the verification of the trial mold, it shortened the development cycle of the mold and others. Qin Qingyi (2020) investigated the influence of multi-factors on the injection mould of multiple indicators. The main optimization indicators were selected warpage and volume shrinkage, orthogonal experiments were designed, and injection mould simulation was performed on the experimental data. An extreme difference analysis was performed on the results of the simulation of the display cover injection mould. According to the analytical results, it can be concluded that the degree of influence of the selected process parameters of the injection mould of the display cover on the optimization indexes. Huang Haisong (2019) adopted grey correlation analysis to disassemble the issue of multi-objective optimization into multiple single-objective optimization. They analyzed and determined the size of the weight coefficients accounted for by each evaluation index, which constructed a second-order prediction model. By adopting the response surface method to resolve the optimization issue of injection mould process parameters, and carrying out the trial mold experiment, the evaluation indexes obtained by this optimization method are all substantially lower. Saad M. S. Mukras (2019) took into account the multi-parameter and multi-indicator issues and calculated the two metrics of warpage and volumetric shrinkage of injection molded products by

Paper Received December 2024. Revised January 2025. Accepted Febryary 2025. Author for Corresponding: Shanshan Peng

Zhendong Zhang, School of Mechanical Engineering, Anhui Institute of Information Technology, Wuhu, Anhui 241000, China.

Shanshan Peng, School of Mechanical Engineering, Anhui Institute of Information Technology, Wuhu, Anhui 241000, China.

taking the framework of minimizing product defects. They proposed a multi-objective issue to minimize the two defects and solved it with genetic algorithms. The experimental results demonstrated that it was close to the optimization results with a difference of about 7%. Apurba Pathak (2018) proposed multi-objective optimization of process parameters of VCR gasoline engine, designed 27 sets of orthogonal experiments, and conducted multi-objective optimization with grey correlation analysis (GRA) to determine the optimal solution. Finally, analysis of variance (ANOVA) was carried out in conjunction with the simulation results of the orthogonal experiments. Based on the results of the analysis, the degree of influence of each process parameter on the optimization indexes of VCR gasoline engine could be obtained. Vishwanath Panwar (2021) presented an experimental study on optimization of surface roughness of alloy steel turning by response surface methodology and genetic algorithm. Fifteen sets of experiments were carried out in conjunction with Box-Behnken structural matrix. The mathematical framework of surface roughness was designed with the surface response methodology using response surface modeling. At last, genetic algorithm was utilized for optimization of this model and the optimum setting of the process parameters was obtained. Kuldip Singh Sangwan (2017) examined the optimization of machining process parameters with integrated response surface and genetic algorithms, and developed a response surface model for describing the relationship between machining process parameters and optimization metrics. Genetic algorithm was exploited to optimize the model for finding the optimum, thereby reducing the energy consumption of the machining process on the machine tool.

In this paper, the gating system in the injection mould process of the upper bracket of automobile front-end frame is analyzed and designed, and the corresponding injection mould simulation analysis is done based on Moldflow software. Through the reasonable selection of experimental factors and optimization index design orthogonal experiment, combined with the grey relational analysis (GRA) method to do multi-index injection mould process parameter optimization analysis. The response surface model of the optimization index of the key influencing parameters was established, and the genetic algorithm was used to further optimize the injection mould process parameters of the model, the specific process is shown in Figure 1. The upper bracket of automobile front-end frame is injected in the factory, and the optimized injection mould process parameters are set for trial molding. The quality of the molded parts is relatively good, and there are no defects such as short shot and flying side.

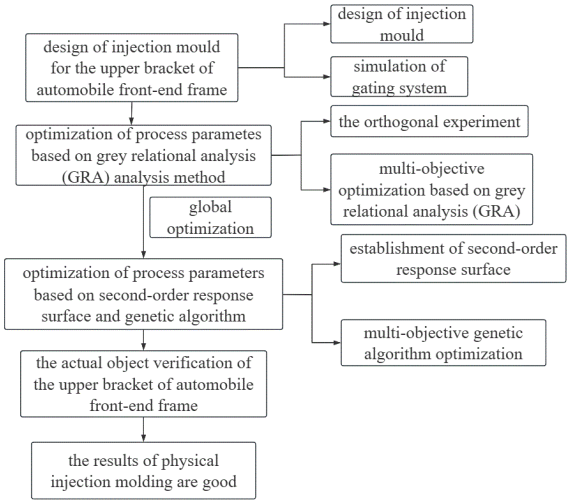


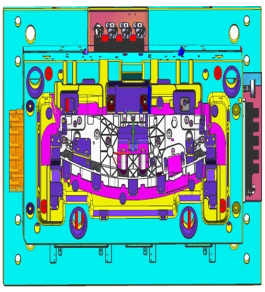
Fig. 1 Process parameter optimization flow chart of the part

GATING SYSTEM DESIGN AND INJECTION MOULD SIMULATION OF THE UPPER BRACKET OF AUTOMOBILE FRONT-END FRAME

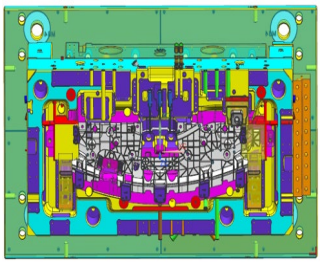
The gating system is a key step in the simulation of injection mould, which needs to be designed according to its actual requirements. The gating system was simulated by Moldflow software, and the reliability and effectiveness of the gating system design were verified.

Design of injection mould for the upper bracket of automobile front-end frame

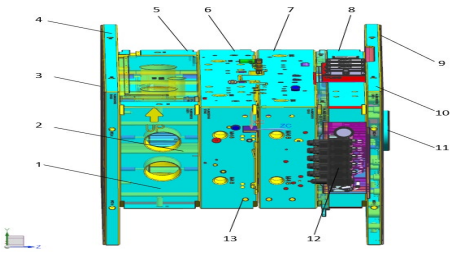
According to the characteristics of the upper bracket of automobile front-end frame, the design and manufacture of the injection mould should be guaranteed within the design life range, and the design of the injection mould should fully combine the specific requirements of the gating system. The three-dimensional diagram of the front mold, the rear mould and the whole mould of the injection mold is shown in Figure 2.



a—Front mould of injection mould



b—Rear mould of injection mould



c—Complete three-dimensional model of injection mould

1- Top needle plate	2- Top needle
3- thermal baffle	4- rear mould base plate
5- quadrant iron	6- convex mould
7- concave mould	8- front mould plate
9- thermal baffle	10- front mould base plate
11- main flow channel	12- hydraulic valve
13- connecting bolt	

Fig. 2 Injection mould for the upper bracket of automobile front-end frame

It can be seen from Figure 2 that the upper bracket of automobile front-end frame is mainly composed of two large parts: the front mould and the rear mould. The front mould is composed of the gating system through which the molten plastic flows, various sliders, concave mould, push rod, concave mould fixing plate, heat insulation plate and molded front mould core. The rear mould is composed of a cooling system for cooling the mould cavity, each thimble in the ejection mechanism, the guide sleeve of the guide column in the guiding mechanism, the convex mould, the heat insulation plate, the convex mould fixing plate and the rear mould kernel.

Import and mesh division of the upper bracket of automobile front-end frame

(1) Import and repair of the model

The upper bracket of automobile front-end frame is designed in CATIA. Firstly, the three-dimensional model is imported into CADdoctor repair software of Moldflow for model simplification, during which some unnecessary rounded corners, chamfers and other fine structures can be removed. This can not only improve the strength of the parts, but also provide convenience for the subsequent meshing and reduce the workload. The simplified model is shown in Figure 3.

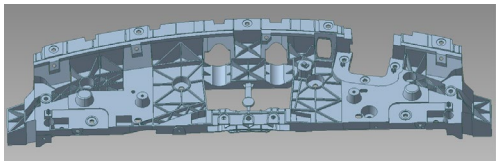


Fig. 3 Simplified model of the upper bracket of automobile front-end frame

(2) Material selection of the upper bracket of automobile front-end frame

The material of the upper bracket of automobile front-end frame is selected by the manufacturer after comprehensive consideration of economy, reliability and practicability. The name is long glass fiber poly-propylene material with a filler content of 30 % mass fraction, referred to as PP-LGF30, which has a low density and conforms to the lightweight route. The specific brand of the material is Sumistran PG3060. Through Moldflow material search, it is found that the manufacturer is Sumitomo Chemical CoMPany, and the recommended process parameters are shown in Table 1.

Table 1 Recommended range of process parameters

mould temperature / ℃	melt temperature range / ℃	absolute maximum melt temperature / ℃	ejection temperature / ℃	maximum shear stress / MPa	maximum shear velocity / s^{-1}
20～80	200～280	300	114	0.25	100000

The material on the upper bracket of automobile front-end frame must have good fluidity, corrosion resistance and other characteristics. Combined with the actual material properties and the recommended range of process parameters, it is proposed to set the mould temperature, melt temperature, dwell time, holding pressure, injection time: 50℃, 250℃, 20 s, 40MPa, 2.5s, other process parameters are used default values. The specific viscosity model curve and PVT curve of Sumistran PG3060 material are shown in Figures 4 and 5.

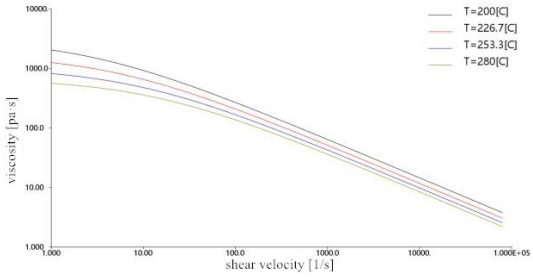


Fig. 4 viscosity curve of PP-LGF30

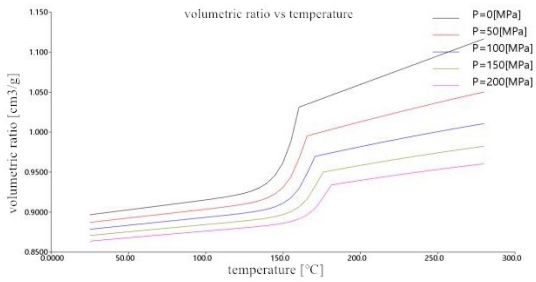


Fig. 5 PVT curve of PP-LGF30

(3) Mesh division and repair

After simplifying and repairing the three-dimensional data model, Autodesk Moldflow Insight (AMI) is used to divide the double-layer mesh. The side length of the double-layer mesh is usually 1.5 ~ 2 times the thickness of the part. Since the basic thickness of the part in this paper is 2.5mm, the global variable length of the mesh is 5.0mm. The important geometric information in the process of meshing generally includes aspect ratio, free edge, orientation, cross and overlap. The double-layer mesh model of the upper bracket of automobile front-end frame is shown in Figure 6, the mesh thickness is shown in Figure 7, and the mesh information is shown in Table 2.

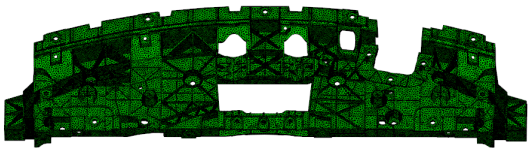


Fig. 6 The mesh model of the upper bracket of automobile front-end frame

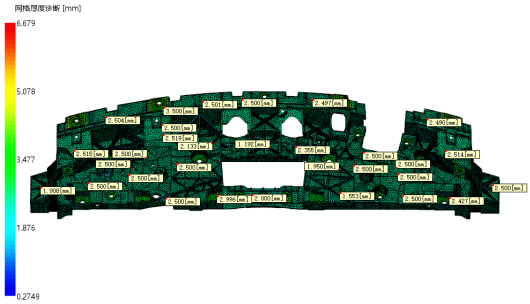


Fig. 7 The mesh thickness of the upper bracket of automobile front-end frame

Table 2 Mesh information after automatic division

maximum aspect ratio	free edge	The incorrectly oriented unit	crossed unit	overlapped unit	mesh matching rate
38.64	0	1095	35	13	90.7%

From Table 2, it can be seen that the maximum aspect ratio of the mesh is large and needs to be repaired to about 10. In addition, the free edges, the incorrectly oriented unit, crossed and overlapped units in the mesh information must be zero, otherwise the mesh model will be wrong in the analysis. Based on the above information, the repaired mesh information is shown in Table 3.

Table 3 Mesh information after repair

maximum aspect ratio	free edge	The incorrectly oriented unit	crossed unit	overlapped unit	mesh matching rate
11.91	0	0	0	0	92.7%

It can be seen from Table 3 that the quality of the repaired mesh has reached the double-layer analysis requirements of the upper bracket of automobile front-end frame.

Simulation of gating system of the upper bracket of automobile front-end frame

The gating system is an important channel for conveying molten plastic from the nozzle of the injection mould machine to the mould cavity. The gate and flow passage are the main components of the gating system. The quality of the gate determines the quality of the gating system, and the quality of the gating system determines the quality of the injection products. Therefore, the design of the gating system is an important part of the mold design.

According to the actual requirements, the design point gate diameter D = 2 mm; the diameter of the small end of the main flow passag is D1 = 10 mm, and the diameter of the large end is D2 = 22

mm. The diameter of the split flow passag D3 = 22 mm, the diameter of the large end of the vertical flow passag D4 = 22 mm, and the diameter of the small end D5 = 10 mm. The gating system is shown in Figure 8.

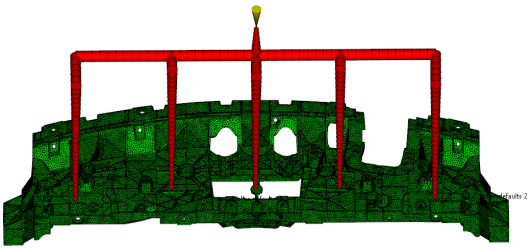


Fig. 8 Gating system of the upper bracket of automobile front-end frame

In order to verify whether the gating system designed above is reasonable, the filling-packing-warping is selected in the analysis sequence of Moldflow software, and the injection mould simulation of the gating system of the upper bracket of automobile front-end frame is carried out. The injection mould process parameters were set as follows: melt temperature 250 °C, mould temperature 50 °C, filling time 2.5 s, holding pressure 40 MPa, dwell time 20 s. The analysis results are shown in the following Figures 9, 10, 11, 12, 13 and 14.

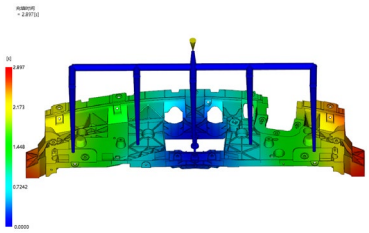


Fig. 9 Filling time in simulation

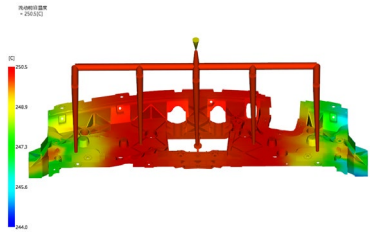


Fig. 10 The flow front temperature in the simulation

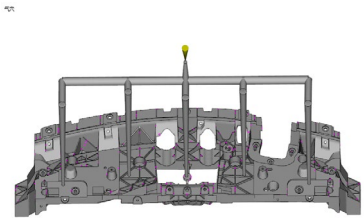


Fig. 11 Cavitation in simulation

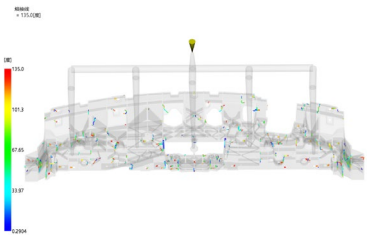


Fig. 12 Welding line in simulation

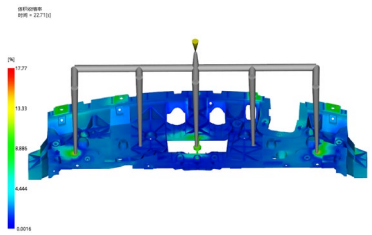


Fig. 13 Volumetric shrinkage rate in simulation

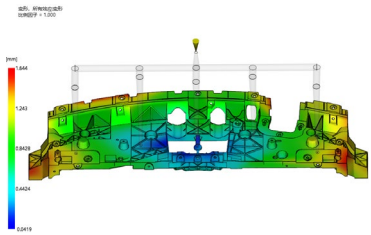


Fig. 14 Warpage deformation amount in simulation

Through the above simulation of the cloud Figures 9, 10, 11, 12, 13 and 14 can be obtained, the upper bracket of automobile front-end frame filling is relatively complete ; the temperature difference of the flow front temperature is relatively small, that is, within 20°C; the cavitation generated during the injection filling process can be discharged by itself through the parting surface ; because the upper bracket is not the appearance part, the requirement for the welding line is not high. After the filling is completed, the volume shrinkage rate and warpage deformation amount of the upper bracket of automobile front-end frame can be obtained as 17.77% and 1.644 mm, respectively. In summary, the gating system design of the upper bracket of automobile front-end frame is reasonable.

OPTIMIZATION OF PROCESS PARAMETERS OF THE UPPER BRACKET OF AUTOMOBILE FRONT-END FRAME BASED ON GREY RELATIONAL ANALYSIS (GRA)

ANALYSIS METHOD

The orthogonal experiment is used to optimize the process parameters of a single evaluation index for the upper bracket of automobile front-end frame, and the multi-index process parameters are optimized by combining the grey relational analysis (GRA) analysis method.

The orthogonal experiment

(1) Targets of experiment

In this paper, the thickness of the upper bracket of automobile front-end frame is not very uniform, so it will produce warpage deformation amount during the injection mould process. The volume shrinkage rate of each part of the plastic part is the main reason for its warpage deformation amount. At the same time, the plastic part needs to achieve a certain surface finish and assembly accuracy. Therefore, the volume shrinkage rate and warpage deformation amount of the upper bracket of automobile front-end frame are used as Targets of experiment.

(2) Experimental factors

The injection mould of the upper bracket of

automobile front-end frame is affected by many factors. Through consulting the literature, it is found that the mould temperature, melt temperature, holding pressure and holding time are the main factors affecting the volume shrinkage rate and warpage deformation amount of the product during the injection mould process. These four main factors are used as experimental factors. Mould temperature, melt temperature, holding pressure and dwell time are represented by letters A, B, C and D respectively.

(3) Selection of orthogonal table

Select the appropriate orthogonal table according to the experiment index and experiment factors. Here, the orthogonal table of equal level is selected, that is, each influencing factor of the orthogonal table has the same level number, in the form of $L_m(a^b)$, where, “m”-the number of experiment, "a"-the number of levels of the experiment, "b"-the number of factors of the experiment. By evaluating the indexes and factors of this experiment, the $L_{25}(5^4)$ orthogonal table was selected, that is, 25 groups of injection mould process parameters with 4 factors and 5 levels. According to the range of process parameters recommended by PP-LGF30 material in Moldflow, the level range of factors is determined. The level settings selected for each factor are shown in Table 4. The 25 groups of orthogonal experiments were combined in Moldflow software for injection mould simulation. According to the simulation results, the volume shrinkage rate and warpage deformation amount of the upper bracket of automobile front-end frame can be obtained as shown in Table 5.

Table 4 The level factor setting of the experiment

level	factors			
	A mould temperature / ℃	B melt temperature / ℃	C holding pressure / MPa	D dwell time / s
1	30	230	30	10
2	40	240	35	15
3	50	250	40	20
4	60	260	45	25
5	70	270	50	30

able 5 Orthogonal experimental design and results

Serial number	experimental factors				Targets of experiment	
	A / ℃	B / ℃	C / MPa	D / s	volume shrinkage rate / %	warpage deformation amount / mm
1	30	230	30	10	16.55	1.679
2	30	240	50	30	17.24	1.534
3	30	250	45	25	17.76	1.549
4	30	260	40	20	18.26	1.580
5	30	270	35	15	18.75	1.624
6	40	230	40	25	16.77	1.599
7	40	240	35	20	17.27	1.627
8	40	250	30	15	17.75	1.672
9	40	260	50	10	18.21	1.680
10	40	270	45	30	18.71	1.571
11	50	230	50	15	16.75	1.654
12	50	240	45	10	17.26	1.672
13	50	250	40	30	17.77	1.612
14	50	260	35	25	18.27	1.633
15	50	270	30	20	18.75	1.666
16	60	230	35	30	16.78	1.675
17	60	240	30	25	17.27	1.697
18	60	250	50	20	17.74	1.654
19	60	260	45	15	18.23	1.672
20	60	270	40	10	18.74	1.815
21	70	230	45	20	16.77	1.705
22	70	240	40	15	17.28	1.727
23	70	250	35	10	17.77	1.851
24	70	260	30	30	18.28	1.703
25	70	270	50	25	18.69	1.649

Multi-objective optimization based on grey relational analysis (GRA)

Through the grey relational analysis (GRA) analysis method, a set of injection mould process parameters that simultaneously achieve the best volume shrinkage rate and warpage deformation amount were found from the experimental combination of orthogonal experiments.

(1) Grey relational analysis (GRA) steps

a) Determine the analysis sequence:

Reference sequence:

$$Y=Y(k)|k=1,2\cdots n \quad (1)$$

Compare sequence:

$$X_i=X_i(k)|k=1,2\cdots n;\ i=1,2\cdots m \quad (2)$$

In the formula, Y (k) -evaluation index, volume shrinkage rate and warpage deformation amount;

$X_i(k)$-the value of volume shrinkage rate and warpage deformation amount;

k-the number of evaluation indexes;

i- number of groups analyzed.

b) Dimensionless sequence of variables

Initialization:

$$X_i^*(k)=\frac{X_i(k)}{X_i(1)},\ k=1,2\cdots n;\ i=1,2\cdots m \quad (3)$$

In the formula, $X_i^*(k)-$ the value of volume shrinkage rate and warpage deformation amount after initial treatment.

c) Calculation of correlation coefficient

The maximum value of each evaluation index is recorded as a reference sequence, namely

$$y(k)=\max(x_i(x)),\ k=1,2\cdots n;\ i=1,2\cdots m \quad (4)$$

$$\xi_i(k)=\frac{\min_i\min_k|y(k)-x_i(k)|+\rho\max_i\max_k|y(k)-x_i(k)|}{|y(k)-x_i(k)|+\rho\max_i\max_k|y(k)-x_i(k)|} \quad (5)$$

Let $\Delta_i(k)=|y(k)-x_i(k)|$

$$\xi_i(k)=\frac{\min_i\min_k\Delta_i(k)+\rho\max_i\max_k\Delta_i(k)}{\Delta_i(k)+\rho\max_i\max_k|y(k)-x_i(k)|} \quad (6)$$

In the formula, $\xi_i(k)-$the correlation coefficient between volume shrinkage rate and warpage deformation amount.

$\rho\in(0,\infty)$-resolution coefficient, the larger the ρ is, the smaller the resolution is. The specific value range of ρ can be determined according to the situation, which is generally (0,1). When $\rho\le 0.5463$, the resolution is the best, therefore, ρ generally take 0.5.

d) Association calculation

The correlation degree r_i formula is as follows:

$$r_i=\frac{1}{n}\sum_{k=1}^{n}\xi_i(k),\ k=1,2\cdots n \quad (7)$$

In the formula, r_i-the correlation between the volume shrinkage rate and warpage deformation amount.

(2) grey relational analysis (GRA) evaluation

Through analysis, the reference sequence, dimensionless sequence, correlation coefficient sequence and correlation degree can be obtained in turn. Therefore, the data obtained based on grey relational analysis (GRA) analysis are shown in Table 6.

Table 6 grey relational analysis (GRA) analysis results

Serial number	reference sequence		dimensionless sequence		correlation coefficient sequence		correlation degree
	$X_i(1)$	$X_i(2)$	$X_i^*(1)$	$X_i^*(2)$	$\xi_i(1)$	$\xi_i(2)$	r_i
1	16.55	1.679	1.000	1.000	0.333	0.481	0.4070
2	17.24	1.534	1.042	0.914	0.421	0.333	0.3770
3	17.76	1.549	1.073	0.923	0.526	0.344	0.4350
4	18.26	1.580	1.103	0.941	0.692	0.369	0.5305
5	18.75	1.624	1.133	0.967	1.000	0.411	0.7055
6	16.77	1.599	1.013	0.952	0.357	0.386	0.3715
7	17.27	1.627	1.044	0.969	0.426	0.414	0.4200
8	17.75	1.672	1.073	0.996	0.524	0.471	0.4975
9	18.21	1.680	1.100	1.001	0.671	0.481	0.5760
10	18.71	1.571	1.131	0.936	0.965	0.361	0.6630
11	16.74	1.654	1.011	0.985	0.354	0.446	0.4000
12	17.26	1.672	1.043	0.996	0.425	0.471	0.4480
13	17.77	1.612	1.074	0.960	0.529	0.401	0.4650
14	18.27	1.633	1.104	0.973	0.696	0.421	0.5585
15	18.75	1.666	1.133	0.992	1.000	0.461	0.7305
16	16.78	1.675	1.014	0.998	0.358	0.474	0.4160
17	17.27	1.697	1.044	1.011	0.426	0.507	0.4665
18	17.74	1.654	1.072	0.985	0.521	0.446	0.4835
19	18.23	1.672	1.102	0.996	0.679	0.471	0.5750
20	18.74	1.815	1.132	1.081	0.991	0.815	0.9030
21	16.77	1.705	1.013	1.015	0.357	0.521	0.4390

22	17.28	1.727	1.044	1.029	0.428	0.561	0.4945
23	17.77	1.851	1.074	1.102	0.529	1.000	0.7645
24	18.28	1.703	1.105	1.014	0.701	0.517	0.6090

(3) Extreme difference and variance analysis of grey relational analysis (GRA)

The data are obtained by grey relational analysis (GRA) analysis, and the mean and extreme difference are shown in Table 7, the variance is shown in Table 8, and the line chart of grey relational analysis (GRA) extreme difference is shown in Figure 15. The greater the value of the grey relational analysis (GRA), the stronger the correlation with the reference sequence (the maximum value of the evaluation index).

Table 7 Extreme difference analysis of grey relational analysis (GRA)

level	experimental factors			
	A	B	C	D
k1	0.4910	0.4067	0.5421	0.6197
k2	0.5056	0.4412	0.5729	0.5345
k3	0.5204	0.5291	0.5529	0.5207
k4	0.5688	0.5698	0.5120	0.5052
k5	0.6003	0.7393	0.5062	0.5060
R	0.1093	0.3326	0.0667	0.1145

Table 8 Variance analysis of grey relational analysis (GRA)

experimental factors	sum of squars of deviation / S_T	degree of freedom / f_T	mean square value / $\bar{S}_T$	influence degree / %
A	0.042	4	0.010	9.44%
B	0.341	4	0.085	76.63%
C	0.016	4	0.004	3.61%
D	0.046	4	0.011	10.34%
Se	0.445	16		

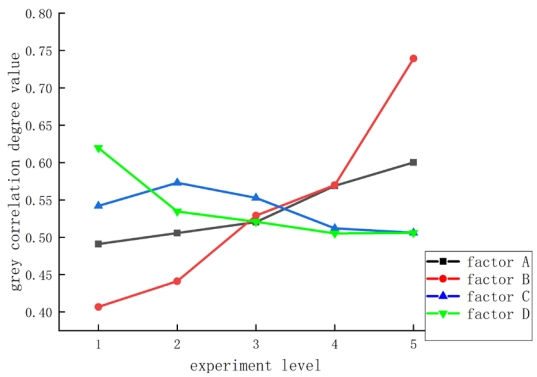


Fig. 15 Extreme difference analysis of grey relational analysis (GRA)

From Table 7 and Table 8, it can be seen that the smaller the value of the evaluation index needed in this paper, the better. Therefore, the combination of a set of process parameters with the smallest grey relational analysis (GRA) is A1B1C5D4 (30°C, 230 °C, 50 MPa, 25 s), which corresponds to the optimal set of process parameters. It can be seen from Table 8 that the influence degree of each factor on the evaluation index: melt temperature > dwell time > mould temperature > holding pressure. The injection mould simulation was carried out in Moldflow software, and the volume shrinkage rate and warpage deformation amount were 16.74 % and 1.548 mm, respectively, as shown in Figure 16.

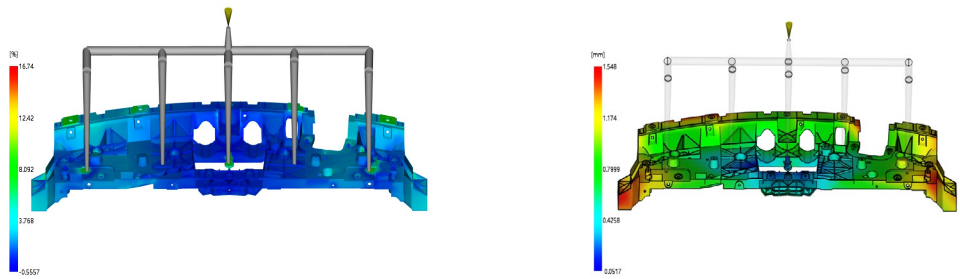


Fig. 16 Process parameter combination A1B1C5D4 (30 °C, 230 °C, 50 MPa, 25 s) analysis results

Based on the multi-index optimization of the grey relational analysis (GRA) method, although the volume shrinkage rate and warpage deformation amount are not as small as the single index optimization, the two indicators have been taken into account and the optimization effect is obvious, which also proves that the grey relational analysis (GRA) method has a good effect in multi-index optimization.

OPTIMIZATION OF PROCESS

PARAMETERS OF THE UPPER BRACKET OF AUTOMOBILE FRONT-END FRAME BASED ON SECOND-ORDER RESPONSE SURFACE AND GENETIC ALGORITHM

The response surface method mainly takes the factor as the independent variable and the evaluation index as the dependent variable, so as to establish the function expression between the factor and the evaluation index, that is, the mathematical model, so as to make the results more comprehensive and complete. Finally, the response surface method is combined with the genetic algorithm to optimize the process parameters of the upper bracket of automobile front-end frame.

Response surface model

The response surface model mainly reflects a function of the quantitative relationship between the independent variables and the dependent variables. Considering that there are the existence of linear terms and interactions between the various process parameter variables in the injection mould process, the second-order polynomial function is used to approximate the response surface model. In the equal diameter experiment, the $y(x_i)$ values at each level can be obtained according to the factors x_i, and then the experiment data are fitted. Therefore, the second-order polynomial is obtained as follows :

$$\hat{y}(x) = \alpha_0 + \sum_{i=1}^{k} \alpha_i x_i + \sum_{i=1}^{k} \alpha_i x_i^2 + \sum_{ij} \sum_{i<j}^{k} \alpha_{ij} x_i x_j + \varepsilon_y \quad (8)$$

In the formula, $\alpha_0, \alpha_i, \alpha_{ii}, \alpha_{ij}$ are the coefficients of each item, to be solved;

ε_y - fitting coefficient, and obey the normal distribution $N(0, \sigma_y^2)$.

The coefficient matrix of the second-order polynomial is obtained by the least square method, as follows:

$$\hat{\alpha} = (x^T x)^{-1} x^T y \quad (9)$$

x - the numerical matrix after calculation.

Establishment of second-order response surface

This section mainly selects the key factors that affect the injection mould quality of the upper bracket of automobile front-end frame, establishes an octagonal equal diameter experiment, and uses Moldflow software to simulate the experimental data to obtain the experimental results. The second-order response surface formula of the volume shrinkage rate and warpage deformation amount of the upper bracket of automobile front-end frame is established.

Through the grey relational analysis (GRA) analysis, it can be concluded that the melt temperature and dwell time are the key factors affecting the volume shrinkage rate and warpage deformation amount of the upper bracket of automobile front-end frame. Therefore, the octagonal equal diameter experiment was designed with the melt temperature of 230 ℃ and the dwell time of 25 s as the center. The range of melt temperature and dwell time was $220\,℃ \le T \le 240\,℃$ and $20s \le t \le 30s$, respectively. The variables are encoded to obtain the following formula, and the octagonal equal diameter experiment is shown in Figure 17. The mould temperature is 30 ℃ and the holding pressure is 50 MPa.

$$x_1 = \frac{T-230}{10} \quad (10)$$

$$x_2 = \frac{t-25}{5} \quad (11)$$

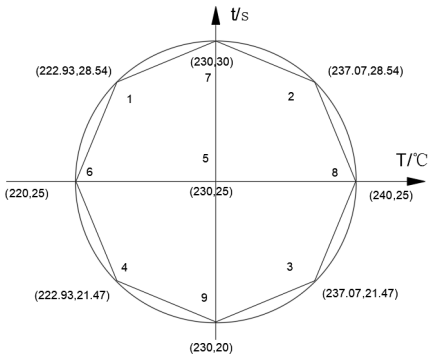


Fig. 17 Octagon equal diameter experiment

The octagonal equal diameter experiment was converted by the variables between the codes, and a total of 9 sets of random experimental data were obtained. The other process parameters, such as mould temperature and holding pressure, remained unchanged after the optimization analysis of grey relational analysis (GRA). Moldflow was used to simulate the combination of these 9 sets of process parameters. The results are shown in Table 9.

Table 9 Octagonal equal diameter experiment and experimental results

serial number	experimental factors		variable coding		experimental results	
	melt temperature / ℃	dwell time / s	x_1	x_2	volume shrinkage rate y_1 / %	warpage deformation amount y_2 / mm
1	222.93	28.54	-0.707	0.707	16.38	1.535
2	237.07	28.54	0.707	0.707	17.09	1.529
3	237.07	21.47	0.707	-0.707	17.09	1.532
4	222.93	21.47	-0.707	-0.707	16.38	1.537
5	230	25	0	0	16.74	1.548

6	220	25	-1	0	16.23	1.542
7	230	30	0	1	16.74	1.529
8	240	25	1	0	17.24	1.534
9	230	20	0	-1	16.74	1.537

According to the experiment results of Table 9, combined with formulas (1) and (2), the response surface model of volume shrinkage rate and warpage deformation amount can be obtained.

(1) Second-order response surface model of volume shrinkage rate

The coefficient matrix can be obtained by the above formula:

$$x=\begin{bmatrix} & x_1 & x_2 & x_1^2 & x_2^2 & x_1x_2 \\ 1 & -0.707 & 0.707 & 0.4998 & 0.4998 & -0.4998 \\ 1 & 0.707 & 0.707 & 0.4998 & 0.4998 & 0.4998 \\ 1 & 0.707 & -0.707 & 0.4998 & 0.4998 & -0.4998 \\ 1 & -0.707 & -0.707 & 0.4998 & 0.4998 & 0.4998 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 & 1 & 0 \end{bmatrix},\quad y_1=\begin{bmatrix} 16.38 \\ 17.09 \\ 17.09 \\ 16.38 \\ 16.74 \\ 16.23 \\ 16.74 \\ 16.24 \\ 16.74 \end{bmatrix}$$

Calculate the fitting coefficient :

$$\hat{\alpha}_1=\begin{bmatrix} \hat{\alpha}_0 \\ \hat{\alpha}_1 \\ \hat{\alpha}_2 \\ \hat{\alpha}_{11} \\ \hat{\alpha}_{22} \\ \hat{\alpha}_{12} \end{bmatrix}=(x^Tx)^{-1}x^Ty_1=\begin{bmatrix} 16.7401 \\ 0.1688 \\ 0.0847 \\ -0.4413 \\ 0.0637 \\ 0.4793 \end{bmatrix}$$

The response surface model of volume shrinkage rate is obtained:

$$\hat{y}(x)=16.7401+0.1688x_1+0.0847x_2 -0.4413x_1^2+0.0627x_2^2 +0.4793x_1x_2$$

(2) Second-order response surface model of warpage deformation amount

The coefficient matrix can be obtained by the above formula:

$$x=\begin{bmatrix} & x_1 & x_2 & x_1^2 & x_2^2 & x_1x_2 \\ 1 & -0.707 & 0.707 & 0.4998 & 0.4998 & -0.4998 \\ 1 & 0.707 & 0.707 & 0.4998 & 0.4998 & 0.4998 \\ 1 & 0.707 & -0.707 & 0.4998 & 0.4998 & -0.4998 \\ 1 & -0.707 & -0.707 & 0.4998 & 0.4998 & 0.4998 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 & 1 & 0 \end{bmatrix},\quad y_2=\begin{bmatrix} 1.535 \\ 1.529 \\ 1.532 \\ 1.537 \\ 1.530 \\ 1.542 \\ 1.529 \\ 1.534 \\ 1.537 \end{bmatrix}$$

Calculate the fitting coefficient:

$$\hat{\alpha}_2=\begin{bmatrix} \hat{\alpha}_0 \\ \hat{\alpha}_1 \\ \hat{\alpha}_2 \\ \hat{\alpha}_{11} \\ \hat{\alpha}_{22} \\ \hat{\alpha}_{12} \end{bmatrix}=(x^Tx)^{-1}x^Ty_2=\begin{bmatrix} 1.5300 \\ -0.0033 \\ -0.0035 \\ 0.0073 \\ 0.0023 \\ -0.0034 \end{bmatrix}$$

The response surface model of warpage deformation amount is obtained:

$$\hat{y}(x)=1.5300-0.0033x_1-0.0035x_2 +0.0037x_1^2+0.0023x_2^2 -0.0034x_1x_2$$

Analysis of variance and significance inspection

When $F>F(2,6,0.01)=10.9$, under the constraint of horizontal $\alpha=0.01$, the fitting degree of the established second-order response surface is higher.

(1) Analysis of variance and inspection of volume shrinkage rate

After calculation, the second-order response surface fitting variance of the volume shrinkage rate can be obtained as shown in Table 10.

Table 10 The second-order response surface fitting variance of volume shrinkage rate

source	sum of fluctuation square	degree of freedom	F valued
fitting	S_R=0.1352	f_R=2	F=21.18
residual error	S_e=0.0527	f_e=6	
summation	S_T=0.1826	f_T=8	

(Note: When F inspection is used, $\alpha=0.01, F_{2,6}=10.9$.)

From the analysis of Table 10, it can be seen that the second-order response surface fitting variance of the volume shrinkage rate of the upper bracket of automobile front-end frame is 21.18, so the second-order response surface fitting degree is high.

Based on the second-order response surface model, $R=\{-1\le x_i\le 1, i=1,2\}$ in MATLAB, the second-order response surface and contour map of the volume shrinkage rate of the upper bracket of automobile front-end frame are drawn. As shown in Figure 18, for the parts, the smaller the volume shrinkage rate, the more conducive to assembly.

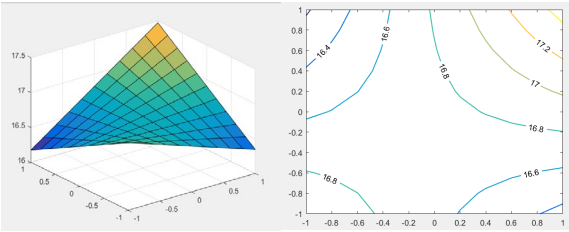


Fig. 18 Second-order response surface and contour map of volume shrinkage rate

(2) Analysis of variance and inspection of warpage deformation amount

After calculation, the fitting variance of the second-order response surface of the warpage deformation amount can be obtained as shown in Table 11.

Table 11 Fitting variance of second-order response surface of warpage deformation amount

source	sum of fluctuation square	degree of freedom	F valued
fitting	S_R=0.0087	f_R=2	F=42.08
residual error	S_e=0.0041	f_e=6	
summation	S_T=0.0114	f_T=8	

（Note: When F inspection is used, $\alpha = 0.01, F_{2,6} = 10.9$.）

From the analysis of Table 11, it can be seen that the second-order response surface fitting variance of the warpage deformation amount of the upper bracket of automobile front-end frame is 42.08, so the second-order response surface fitting degree is high.

Based on the second-order response surface model, $R = \{-1 \le x_i \le 1, i = 1,2\}$ in MATLAB, the second-order response surface and contour map of the warpage deformation amount of the upper bracket of automobile front-end frame are drawn. As shown in Figure 19, for the parts, the smaller the warpage deformation amount, the more conducive to assembly.

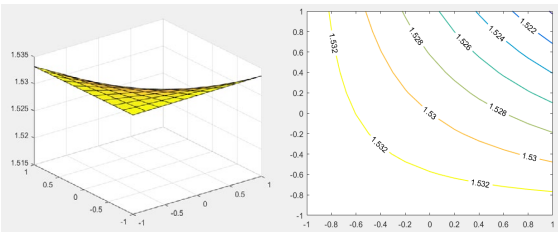


Fig. 19 Second-order response surface and contour map of warpage deformation amount

(3) Comparative analysis of experimental values and fitting values of volume shrinkage rate and warpage deformation amount

By comparing the experimental values of volume shrinkage rate and warpage deformation amount with the values fitted by the second-order response surface model, Table 12 can be obtained, and the line charts of volume shrinkage rate and warpage deformation amount are shown in Figures 20 and 21, respectively. The errors of volume shrinkage rate and warpage deformation amount are shown in Figures 22 and 23.

Table 12 Comparative analysis of fitting value and experimental value of volume shrinkage rate and warpage deformation amount

serial number	y_1 experimental value	y_2 experimental value	y_1 fitting value	y_2 fitting value	the error between y_1 experimental value and y_1 fitting value	the error between y_2 experimental value and y_2 fitting value
1	16.38	1.535	16.25	1.535	0.13	0.000
2	17.09	1.529	16.97	1.526	0.12	0.003
3	17.09	1.532	16.37	1.536	0.72	-0.004
4	16.38	1.537	16.61	1.535	-0.23	0.002
5	16.74	1.530	16.74	1.530	0.00	0.000
6	16.23	1.542	16.13	1.537	0.10	0.005
7	16.74	1.529	16.89	1.529	-0.15	0.000
8	17.24	1.534	16.47	1.530	0.77	0.004
9	16.74	1.537	16.72	1.536	0.02	0.001

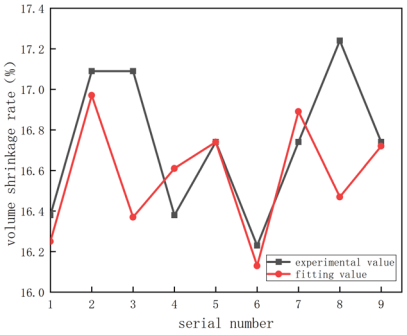


Fig. 20 Comparison diagram of fitting value and experimental value of volume shrinkage rate

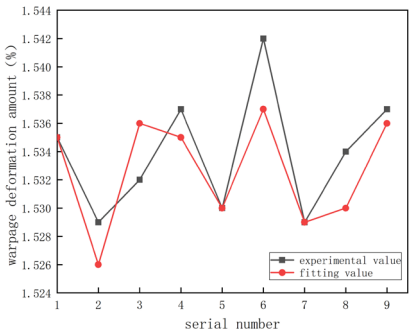


Fig. 21 Comparison diagram of fitting value and experimental value of warpage deformation amount

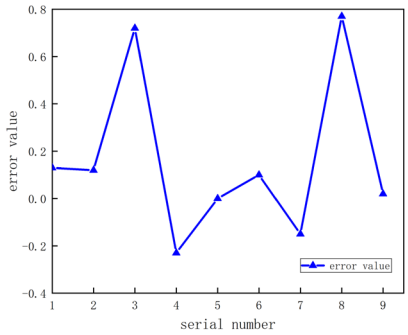


Fig. 22 The error diagram between experimental value and fitting value of volume shrinkage rate

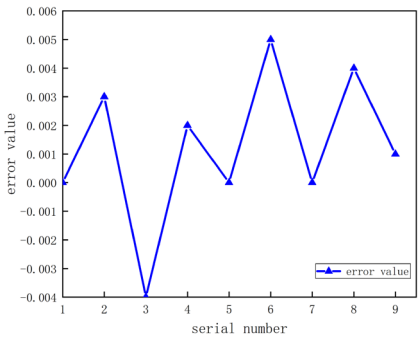


Fig. 23 The error diagram between experimental value and fitting value of warpage deformation amount

In summary, the error of the second-order response surface model fitting of the volume shrinkage rate is within ± 0.8, and the error of the second-order response surface model fitting of the warpage deformation amount is within ± 0.005, which again verifies that the second-order response surface model fitting effect is better.

Second-order response surface analysis to find the optimal solution

In order to obtain a set of solutions with the optimal volume shrinkage rate and warpage deformation amount at the same time, the contour maps of volume shrinkage rate and warpage deformation amount are superimposed in MATLAB, and the obtained contour superposition map is shown in Figure 24.

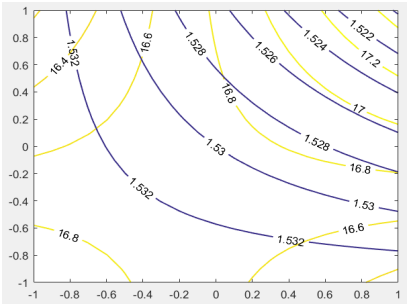


Fig. 24 Superposed diagram of volume shrinkage rate and warpage deformation amount response surface contour

It can be concluded from Figure 24 that in the interval $-1 \le x_1 \le -0.3, 0.4 \le x_2 \le 1$, the volume shrinkage rate and warpage deformation amount of the upper bracket of automobile front-end frame can be relatively optimal at the same time.

Multi-objective genetic algorithm optimization

This section mainly gives a simple overview of the genetic algorithm and its specific implementation process; the second-order response surface formula is combined with the genetic algorithm to perform multi-objective optimization on the upper bracket of automobile front-end frame to obtain the best injection mould process parameters.

(1) Implementation process of genetic algorithm

According to the above formula of the response surface model, it can be seen that the influence of the experiment factors on the volume shrinkage rate is greater than the warpage deformation amount, so the objective function and constraint conditions of the multi-objective optimization of the upper bracket of automobile front-end frame are obtained.

$$F = min\{y_1 + y_2\} = \omega_1 y_1 + \omega_2 y_2 \tag{12}$$

$$s.t.\begin{Bmatrix} -1 \le x_1 \le -0.3 \\ 0.4 \le x_2 \le 1 \end{Bmatrix} \tag{13}$$

In the formula, y_1, y_2 - the volume shrinkage rate and warpage deformation amount of the upper bracket of automobile front-end frame;

ω_1, ω_2 - the weight coefficients of y_1, y_2. In this paper, take $\omega_1 = 0.8, \omega_2 = 0.2$;

x_1 - the melt temperature coding range;

x_2 - the dwell time coding range;

(2) Process parameter optimization based on genetic algorithm

Based on the second-order response surface model, and combined with genetic algorithm, the objective function M file is defined in MATLAB. The population size is 100, the maximum number of evolutionary generations is 200, the number of termination generations is 200, the crossover probability is 0.8, the mutation probability is 0.15, and the deviation of the fitness function is 1e-100. The iterative curve obtained is shown in Figure 25.

It can be seen from Figure 25 that the iterative curve begins to converge after 18 iterations, and the fitness value is 17.5298, which is the minimum value of the objective function. At this time, x_1 and x_2 are -0.83 and 0.86 respectively under the coding variables. After the conversion of the coding variables, the corresponding melt temperature is 221.7 °C and the dwell time is 29.3 s. Therefore, a set of process parameters are obtained: melt temperature 221.7 °C, mould temperature 30 °C, holding pressure 50 MPa and dwell time 29.3 s. Moldflow was used to simulate the injection mould of this set of process parameters, and the results were shown in Figure 26.

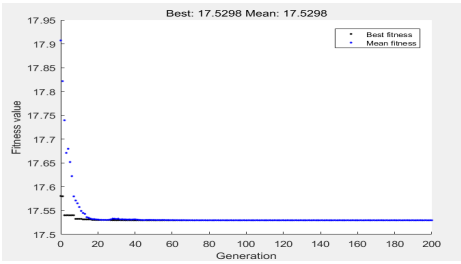


Fig. 25 Iteration curve of genetic algorithm

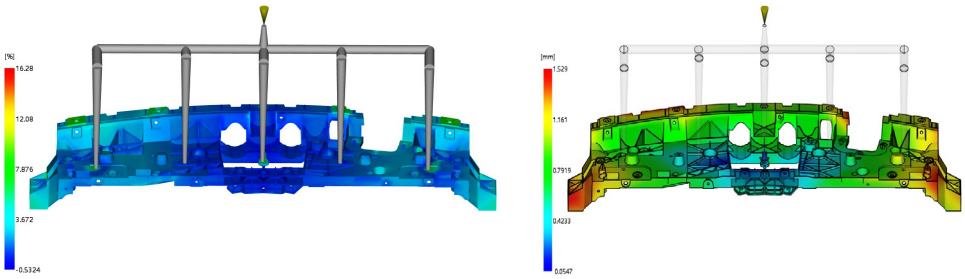


Fig. 26 Simulation results of optimal process parameters combination

From the simulation cloud diagram of Figure 26, it can be obtained that the volume shrinkage rate of the upper bracket of automobile front-end frame is 16.28 %, and the warpage deformation amount is 1.529 mm. Compared with the optimization of grey relational analysis (GRA), the optimization results in this section are relatively better, and it also shows that the genetic algorithm optimization has a good effect.

THE ACTUAL OBJECT VERIFICATION OF THE UPPER BRACKET OF AUTOMOBILE FRONT-END FRAME

In order to verify whether the actual production of the upper bracket is consistent with the CAE simulation results, this section has carried out actual production verification to inspecte the rationality of the design optimization. After the product design is completed, the correctness of the theoretical method can be inspected by actual manufacturing. Therefore, this section will carry out actual object injection mould of the upper bracket of automobile front-end frame.

Preparation before actual object injection mould

(1) injection mould machines and mould

The equipment manufacturer used in this experiment is Guangdong Yizhimi Precision Injection Technology Co., Ltd. The name and model of the injection mould machine are two-plate energy-saving injection mould machine and UN2100D-1U14500; the injection mould machine and mould are shown in Figure 27. The injection mould machine equipment parameters are shown in Table 13.

Table 13 Main performance parameters of injection mould machine

main technical parameters	numerical magnitude	unit
double alloy screw diameter	125	mm
theoretical injection volume	7363	cm3
actual injection volume	6774	g
injection rate	1060	cm3/s
maximum injection speed	86	mm/s
injection pressure	164	MPa
screw length and diameter ratio L / D	20	/
injection stroke	650	mm
maximum screw speed	112	r/min
clamping mould force	21000	KN
maximum mould thickness	1700	mm
minimum mould thickness	800	mm
ejecting force	460	KN

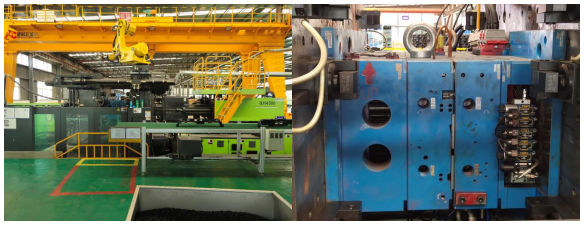


Fig. 27 Physical drawing of injection mould machine and mould

(2) Preparing before trial moulding

The plastic particles PP-LGF30 were placed in a dryer at a temperature of 75 °C -85 °C for 4 hours to remove excess water from the particles. The particles are shown in Figure 28;

The mould is installed on the plate energy-saving injection mould machine model UN2100D-1U14500, and then the complete working process of the mould, such as mould opening, mould closing and core pulling, is carried out, so that the mould can be accurately installed on the injection mould machine; Clean the barrel in the injection mould machine to prevent other materials present in the barrel from affecting the results of this trial moulding.

Fig. 28 Plastic particles PP-LGF30

(3) Setting of process parameters

By optimizing the molding process parameters of the upper bracket of automobile front-end frame from the previous chapters, the specific melt temperature is 221.7 °C, the mould temperature is 30 °C, the holding pressure is 50 MPa, and the dwell time is 29.3 s. During the injection mould period, a period of holding pressure is used, and the injection mould engineer inputs its parameters into the injection mould machine and sets other parameters.

Results of actual object injection mould

The parts after injection mould are shown in Figure 29. It is found that the quality of the parts is relatively good, and there are no injection defects such as short shot, incomplete filling and flying side. The parts are placed on a special inspection instrument to inspecte whether the size of each installation point is qualified. After measurement, it is found that the size of each installation point of the parts is within the allowable range of variation, so the parts are qualified, which further verifies the rationality of the design and optimization of the upper bracket of automobile front-end frame.

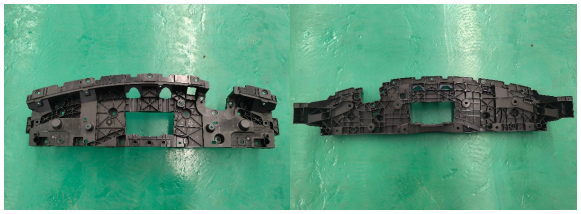


Fig. 29 The physical picture after injection mould

CONCLUSION

In this paper, the upper bracket of automobile front-end frame was taken as the research object. Based on Moldflow, the injection mould simulation of the upper bracket of automobile front-end frame was completed. A variety of optimization methods were used to optimize the injection mould process parameters, and the optimal injection mould process parameters were obtained. The rationality of the design optimization were verified by experiments.

(1) The three-dimensional model of the injection mould for the upper bracket of automobile front-end frame was introduced. The gating system in the injection mould process of the upper bracket of automobile front-end frame was designed. The feasibility of the gating system design was verified by Moldflow injection simulation.

(2) The main variable factors of the experiment were mould temperature, melt temperature, pacing pressure and dwell time. The main optimization indexes of the experiment were volume shrinkage rate and warpage deformation amount. The multi-objective optimization of the upper bracket of automobile front-end frame was carried out by using the grey relational analysis (GRA) method. A set of injection mould process parameters with the smallest volume shrinkage rate and warpage deformation amount at the same time were obtained. According to the variance analysis, the influence degree of each factor on the evaluation index was obtained.

(3) The second-order response surface model of octagonal equal diameter experiment and optimization index centered on the key influencing factors of melt temperature and dwell time was established. The second-order response surface model and genetic algorithm were combined to optimize and solve the multi-objective optimization, and the optimal injection mould process parameters were obtained.

(4) The upper bracket of automobile front-end frame of the designed and optimized was injected into the actual object. The quality of the parts obtained from the trial mould was relatively good, which provides a guiding role for the actual production.

AUTHOR CONTRIBUTIONS

Zhendong Zhang had made substantial contributions to design, experimental research, data collection and result analysis; Shanshan Peng made critical changes to important academic content; Hu Wu made the final review and finalization of the articles to be published.

DATA AVAILABILITY

The data used to support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

FUNDING STATEMENT

This article belongs to the major projects of the "Major Natural Science Foundation of Anhui Province Universities Project (KJ2021ZD0144)." This article belongs to the project of the "Anhui Province First-class Undergraduate Major Construction Project((2020ylzyjsd02)."

REFERENCES

Al-Mufadi F A, Mukras S, Omar H M. Experimental-based multi-objective optimization of injection mould process parameters[J]. Arabian Journal for Science and Engineering, 2019, 44(9): 7653-7665.

Alrweili H, Georgiou S, Stylianou S. A new class of second-order response surface designs[J]. IEEE Access, 2020, 8: 115123-115132.

Anwar V, PKumar K V P, Sharma D K, et.al. Experimental investigations and optimization of surface roughness in turning of 36 alloy steel using response surface methodology and genetic algorithm[J]. Materials Today: Proceedings, 2021, 46: 6474-6481.

Babu K B N. Multi Objective Optimization of Turning Operation Parameters for Aluminium Alloy Using Grey Relational Analysis Method[J]. Materials Science Forum, 2024, 7168 43-49.

Cao Yanli, Fan Xiying, Qin Qingyi, et al. Research on Multi-Objective Influencing Factors of injection mould Quality Based on Orthogonal Experiment[J]. Plastics Science and Technology, 2020, 48(10): 17-20.

Choudhury P K, Dutta R K, Pathak A. Taguchi-grey relational based multi-objective optimization of process parameters on the emission and fuel consumption characteristics of A VCR petrol engine[J]. Materials Today: Proceedings, 2018, 5(2): 4702-4710.

Chen Li, Ren Xiaohong, Wen Renxing. Design of Casting System for Narrow and Long Thin Wall Parts Based on Moldflow[J]. Plastics, 2021, 50(3): 121-124.

Fu Chao, Huang Yao. Optimization of Injection Mold Cooling System for Lamp Shade Based on grey relational analysis (GRA)[J]. Modern Plastics Processing and Applications, 2023, 35(02): 43-46.

Gao Hongchen, Xiao Mengxi, Xue Song, et al. Optimization of Air Purifier Shell injection mould Process Parameters Based on Orthogonal Experiment and BP Neural Network-Genetic Algorithm [J]. Journal of Netshape Forming Engineering, 2023, 15(08): 204-210.

Guo Haoliang, Zhang Wenchao, Zhou Jiwei, et al. Multi-objective Optimization of Sub-dashboard Armrest Base injection mould Process based on Gray Correlation Theory[J]. Engineering Plastics Application, 2022, 50(12): 61-66.

Huang Haisong, Yao Liguo, Zhang Lubin. Multi-objective Optimization of injection mould Process Based on Grey Relational Analysis[J]. Plastics Science and Technology, 2019, 47(1): 104-110.

Huang X, Li M, Zhong X, et al. Parametric study and response surface analysis of hatch sealing structure based on multi-parameter leakage rate prediction model[J]. Nuclear Engineering and Design, 2024, 424, 113309.

Kant G, Sangwan K S. Optimization of machining parameters for improving energy efficiency using integrated response surface methodology and genetic algorithm approach[J]. Procedia CIRP, 2017, 61: 517-522.

Liao Yinghua, Tan Zhou, Xie Jun, et al. Multi－objective optimization design of tool grinder column based on response surface model and genetic algorithm[J]. Manufacturing Technology & Machine Tool, 2021(4): 48-54.

Li Jiacheng, Li Shuaishuai, Zhang Wufei. Optimization of injection mould Process Parameters Based on Response Surface Method[J]. Agricultural Equipment & Vehicle Engineering, 2022, 60(11): 138-141.

Mei Yi, Tang Fangyan, Xue Maoyuan, et al. Multi-objective Optimization of injection mould Process based on Grey Relational Analysis and Establishment of PSO–SVM Prediction Model[J]. Engineering Plastics Application, 2021, 49(3): 58-64.

Mohd A M A, Noorfa I, Raja I, et al. Multiobjective Optimization of Injection Moulding Process Parameters on Mechanical Properties Using Taguchi Method and Grey Relational Analysis[J]. International Journal of Engineering & Technology, 2018, 7(3): 14-14.

Muralikannan R, Senthilkumar S T. Evaluation of recast layer and parametric optimization of EDM process on aluminium based HMMCs using grey relational analysis[J]. Materials

Research Express, 2019, 6(10): 1065a6-1065a6.

Shang Changhua, Tian Mengjie, Wang Jiatao, et al. The Optimization of Injection Mold Process Parameters of Automobile Front Grille Based on Moldflow and Orthogonal Design[J]. Modern Manufacturing Technology and Equipment, 2021, 57(5): 22-23.

Sun Shiren. injection mould Analysis of H12 Protective Cover Based on Moldflow[J]. Modern Manufacturing Technology and Equipment, 2022, 58(2): 83-85.

Wang Mingwei, Zhang Hongwei, Zhang Wenchao, et al. Multi-Objective Optimization of Automotive Fog Lampshade injection mould Process Based on Response Surface Method and Grey Correlation Analysis[J]. Plastics, 2023, 52(06): 122-129.

Wang Xiaobing. Optimization of Process Parameters of Electronic Adapter Molding Based on Multi-Objective Genetic Algorithm[J]. Plastics Science and Technology, 2023, 51(05): 90-94.

Xiong Yue. Lightweight Design of Battery-packEnclosure Based on OrthogonalExperimental Design and Second-order Response Surface Methodology[D]. Chongqing University, 2021.