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Optimization of Injection Molding for Robotic Vacuum Cleaner Housing Components Using an Integrated Mold Flow Analysis and Grey Relational Approach

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Abstract: Taking the sweeping robot shell as the research object, the injection molding simulation was carried out by Moldflow software. Aiming at the volume shrinkage and deformation defects in the injection molding process, the orthogonal test was designed with melt temperature, mold temperature, holding time, holding pressure and cooling time as factors, and the molding process parameters were optimized based on grey correlation analysis. Through the range analysis of the grey correlation degree value, the influence degree of each process parameter on the grey correlation degree value is ranked as follows: melt temperature > mold temperature > holding pressure > holding time > cooling time. The optimum process parameters are as follows: melt temperature 190 °C, mold temperature 70 °C, holding time 12 s, holding pressure 37 MPa, cooling time 16 s. Compared with the default parameters, the X-direction deformation is reduced by 0.343 mm compared with the default process combination, and the volume shrinkage rate is reduced by 3.034 % compared with the default process combination. The results show that the grey correlation theory analysis can obtain a relatively good optimization effect, which can effectively improve the molding quality of the product.

Keywords: Sweeping Robot Shell; Orthogonal Test; Grey Correlation Analysis; Process Optimization; Deformation; Volume Shrinkage Rate.

1. Introduction

As the core structural part and appearance part of the whole machine, the forming quality of the sweeping robot shell directly affects the assembly accuracy, motion performance and user experience of the product. In the injection molding process of thin-walled shell, due to the complex structural characteristics (such as dense stiffeners, surface transition mutations) and the coupling effect of process parameters, it is easy to produce defects such as uneven volume shrinkage and excessive warpage deformation, resulting in abnormal fit clearance of the shell and interference of moving parts, which seriously restricts the product yield[1]. In order to improve the dimensional stability of the shell and reduce the incidence of forming defects, it is urgent to optimize the combination of process parameters through scientific methods[2]. At present, mold flow analysis technology has become an important tool for injection molding process optimization. Domestic and foreign scholars have carried out systematic research through multi-objective integration methods. Ali et al.[3] used orthogonal test to analyze the interaction between melt temperature and mold temperature on warpage and volume shrinkage, and realized multi-objective parameter optimization. Kitayama et al.[4] proposed a method to determine the optimal process parameters in VAIM to simultaneously minimize the warpage and cycle time of sheet products. Ruixia Shan et al.[5] integrated orthogonal test, signal-to-noise ratio and grey correlation analysis, introduced CRITIC weight method to analyze the coupling effect of six parameters such as mold temperature on the shrinkage / warpage of the car lamp shell, and realized process optimization through multi-objective single-objective. Based on Moldflow, Han et al.[6] simulated and diagnosed the warpage of the thin-walled shell of household appliances, and realized the warpage control through the collaborative optimization of the casting / cooling system and the regulation of the temperature field, which effectively reduced the cost of repairing and testing the mold. Zhi Shan[7]proposed a GA-SVR-PSO hybrid optimization framework. The nonlinear surrogate model of warpage deformation and five process parameters was constructed by PSO-SVR, and the global optimization of GA was integrated to reduce the warpage deformation of injection molding by 24.5 % and significantly improve the quality of products.

In this study, the shell of sweeping robot was taken as the object, and the injection molding simulation model was constructed by Moldflow platform. The five-factor orthogonal test was designed with melt temperature, mold temperature, holding time, holding pressure and cooling time as variables. The grey correlation theory is innovatively introduced to transform the volume shrinkage and X-direction deformation into comprehensive grey correlation degree. The sensitivity of parameters is analyzed by range analysis and the optimal process combination is obtained, which provides a theoretical basis for the precision forming of complex thin-walled plastic parts.

2. Initial Analysis of Sweeping Robot Shell

2.1. Model Structure and Injection Molding Materials

Fig.1 is the shell model of the sweeping robot. The maximum size is 347.98mm55.00mm291.02mm, and the volume is 1255.44cm3. From Figure 1, it can be seen that the sweeping robot shell has complex geometric shapes, with more irregular surfaces and bosses. The appearance of plastic parts requires a smooth surface, no obvious weld line, and the volume shrinkage and deformation are required to be as small as possible.

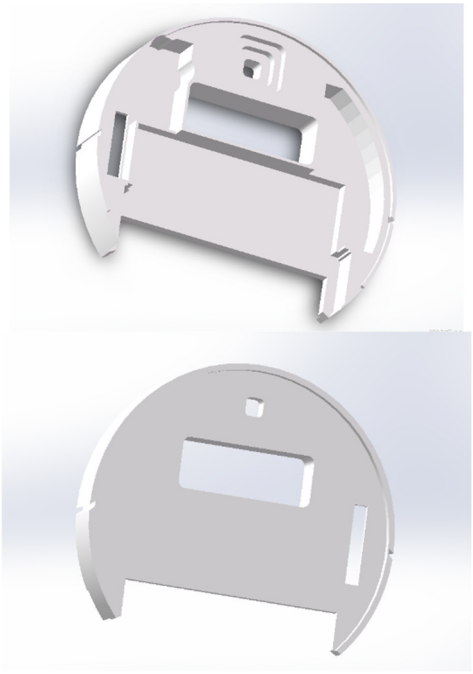
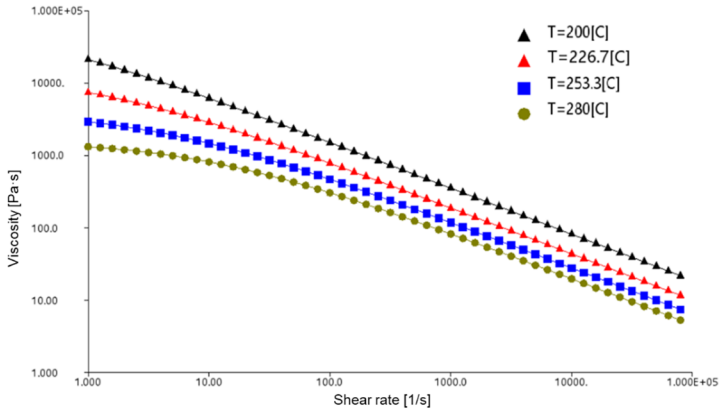


Fig 1. The shell model structure of sweeping robot

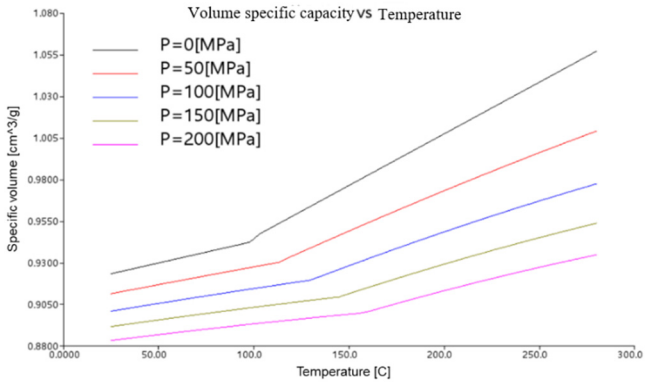
The shell of the sweeping robot is made of acrylonitrile-butadiene-styrene copolymer (ABS) plastic of Monsanto Kasei manufacturer, brand TFX-210.This material has high strength, good toughness and easy processing and molding, and is widely used in automobile manufacturing, electronic appliances, mechanical equipment and other fields. Table 1 is the recommended process parameters for ABS materials, and Figure 2 is the viscosity and volume specific volume curve of the material.

Table 1. Recommended process parameters of ABS material

Parameter	Numerical	Parameter	Numerical
Mold surface temperature /℃	50	Melt temperature/℃	230
Absolute maximum melting temperature /℃	320	Ejection temperature/℃	88
Maximum shear stress /MPa	0.28	Maximum shear rate/s^{-1}	12000



(a) Viscosity curve



(b) Volumetric specific volume curve

Fig 2. Viscosity and volume specific volume curve of ABS material

2.2. Grid Division

The shell model of the sweeping robot built in this work is thick and short, which is suitable for 3D meshing, and the global side length of meshing is 3.00 mm. After the mesh is repaired, there is no folding on the model boundary. There are no inverted tetrahedral units. Tetrahedral mesh refinement is satisfactory. The mesh division is shown in Fig.3. The grid statistical results are shown in Table 2.

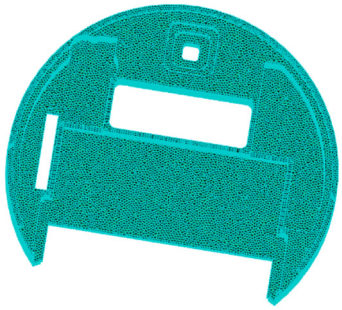


Fig 3. Meshing results of sweeping robot shell

Table 2. Overview of tetrahedral mesh

Parameter	numerical
Total number of nodes	250644
Number of nodes on tetrahedral mesh	250644
Total number of tetrahedrons	1384464
Maximum side length ratio	3.00
Ratio of maximum volume to average volume	19.76
Maximum / average aspect ratio	95.37/3.84
The minimum / maximum angle between the tetrahedrons	0.55/176.33

2.3. Original Parameter Analysis

According to the recommended parameters of the system, the melt temperature is 230 °C, the mold temperature is 50 °C, the holding pressure is 27 MPa, the holding time is 10 s, and the cooling time is 20 s. The analysis of ' filling + holding pressure + cooling + filling + holding pressure + warpage ' is carried out. Figure 7 is the analysis result of the original parameters.

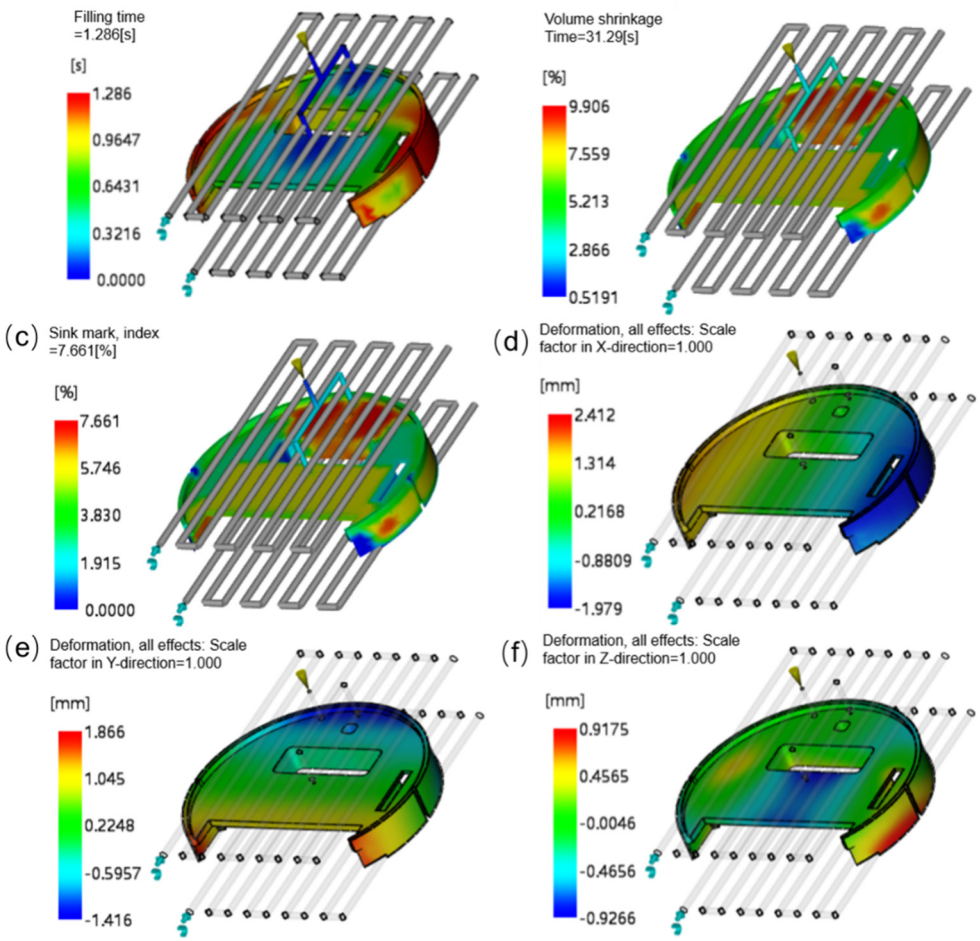


Fig 4. Original parameter analysis results, (a) Filling time, (b) Volume shrinkage, (c) Shrink marks, index, (d) deformation, all effects x direction, (e) Deformation, all effects y direction (f) deformation, all effects z direction

It can be seen from Fig.7 (a) that the plastic part can be filled to the end at 1.286 s, and there is no short shot or hysteresis, indicating that the filling time is more appropriate. It can be seen from Fig.5 (b) that the volume shrinkage of the plastic part is uneven, and the maximum volume shrinkage rate is 9.906 %. The uneven volume shrinkage is easy to cause excessive warpage deformation, so the volume shrinkage is used as one of the optimization indicators. It can be seen from Fig.7 (c) that the product has a higher shrinkage index in the upper middle, which is caused by the product structure and cannot be avoided. From Figure 7 (d) to Figure 7 (f), it can be seen that the deformation, all effects: the maximum displacement in the X direction is 2.412 mm, the deformation, all effects: the maximum displacement in the Y direction is 1.866 mm, the deformation, all effects: the maximum displacement in the Z direction is 0.9175 mm, because the sweeping robot shell needs to be assembled in the X direction, the deformation in the X direction needs to be as small as possible. Therefore, the deformation in the X direction is used as another optimization index.

3. Orthogonal Experimental Design and Analysis of Experimental Results

3.1. Orthogonal Experimental Factor Design

Table 3. Orthogonal test factor level design

Level	Factor				
	Melt temperature (A)/°C	Mold temperature (B)/°C	Pressure duration (C)/s	Packing pressure (D)/MPa	Cooling time (E)/s
1	190	30	8	17	16
2	210	40	9	22	18
3	230	50	10	27	20
4	250	60	11	32	22
5	270	70	12	37	24

According to the analysis results of the default parameters, the deformation and volume shrinkage in the X direction were selected as the optimization objectives, and the melt temperature (A), mold temperature (B), holding time (C), holding pressure (D) and cooling time (E) were selected as

factors, and the orthogonal experimental design was carried out[8]. Without considering the interaction, each factor is set to 5 levels, and Table 3 is the L25 (55) orthogonal test factor level design table.

3.2. Analysis of Orthogonal Experimental Results

The orthogonal test matrix L25 (55) with 5 factors and 5 levels was selected to analyze the molding process of plastic parts based on Moldflow mold flow analysis software, and the X-direction deformation and volume shrinkage after simulation were obtained. Table 4 is the results of L25 (55) orthogonal test, table 5 is the range analysis of volume shrinkage, and table 6 is the range analysis of deformation in X direction.

According to the range analysis of volume shrinkage, the melt temperature has the greatest influence on the volume shrinkage index. The order of the influence degree of the five factors on the volume shrinkage rate from large to small is: melt temperature > holding pressure = holding time > cooling time > mold temperature. The optimum combination of process parameters for the volume shrinkage is A1B4C5D5E1.

According to the range analysis of X-direction deformation, the melt temperature has the greatest influence on the X-direction deformation index. The degree of influence of the five factors on the X-direction warpage deformation index from large to small is: melt temperature > cooling time > holding time > holding pressure > mold temperature. The best combination of process parameters for X direction deformation is A1B2C4D4E1.

Under the orthogonal test, the optimal combination of process parameters affecting volume shrinkage and X-direction deformation is not the same. Therefore, it is necessary to comprehensively analyze the process parameters.

Table 4. L25 (55) Orthogonal experimental results

Test number	Factor						Experiments	
	Melt temperature (A)/℃	Mold temperature (B)/℃	Pressure duration (C)/s	Packing pressure (D)/MPa	Cooling time (E)/s		Volume shrinkage /%	Displacement deformation in X direction /mm
1	190	30	8	17	16		7.772	2.218
2	190	40	9	22	18		7.771	2.177
3	190	50	10	27	20		7.769	2.152
4	190	60	11	32	22		7.151	2.114
5	190	70	12	37	24		7.098	2.081
6	210	30	9	22	20		8.849	2.347
7	210	40	10	27	22		8.845	2.285
8	210	50	11	32	24		8.275	2.218
9	210	60	12	37	16		7.796	2.152
10	210	70	8	17	18		8.850	2.384
11	230	30	10	27	24		9.885	2.414
12	230	40	11	32	16		9.271	2.362
13	230	50	12	37	18		9.039	2.828
14	230	60	8	17	20		9.889	2.498
15	230	70	9	22	22		9.884	2.430
16	250	30	11	32	18		10.530	2.447
17	250	40	12	37	20		10.480	2.450
18	250	50	8	17	22		10.900	2.551
19	250	60	9	22	24		10.900	2.526
20	250	70	10	27	16		10.900	2.452
21	270	30	12	37	22		11.390	2.485
22	270	40	8	17	24		11.910	2.590
23	270	50	9	22	16		11.910	2.589
24	270	60	10	27	18		11.910	2.574
25	270	70	11	32	20		11.480	2.538

Table 5. Range analysis of volume shrinkage

Test number	A	B	C	D	E
S_1	7.512	9.685	9.864	9.864	9.530
S_2	8.523	9.655	9.863	9.863	9.620
S_3	9.594	9.579	9.862	9.862	9.693
S_4	10.742	9.529	9.341	9.341	9.634
S_5	11.720	9.642	9.161	9.161	9.614
R_1	4.208	0.156	0.703	0.703	0.163

Table 6. Range analysis of displacement in X direction

Test number	A	B	C	D	E
S_1^*	2.148	2.382	2.448	2.448	2.355
S_2^*	2.277	2.373	2.414	2.414	2.482
S_3^*	2.506	2.468	2.375	2.375	2.397
S_4^*	2.485	2.373	2.336	2.336	2.373
S_5^*	2.555	2.377	2.400	2.400	2.366
R_1^*	0.407	0.095	0.112	0.112	0.127

4. Optimization of Process Parameters Based on Grey Correlation Analysis

In order to further evaluate the product quality, the signal-to-noise ratio is selected as the evaluation standard of product quality, and the data are statistically analyzed to obtain products with strong anti-interference[9, 10]. The signal-to-noise ratio value is directly proportional to the quality of the product. According to the specific situation, it is divided into eye characteristics, large characteristics and small characteristics[11]. Injection molding products want to get as small as possible warpage deformation value and volume shrinkage to ensure product quality. Therefore, the expected small characteristic is selected, and the calculation formula is:

$$\alpha=-10\lg\left(\frac{1}{n}\sum_{i=1}^{n}x_i^2\right) \tag{1}$$

In formula (1): α is the number of times that each set of tests is to be repeated ; 11 OOV is the test value corresponding to the i th test.

In practical work, the quality of a product is not only measured by one index, sometimes it is considered according to two or more goals, so as to select a reasonable method[8]. The analysis methods commonly used in multi-objective experiments are comprehensive balance method and grey correlation analysis method. The comprehensive balance method is to evaluate a comprehensive score for each test, and the score is analyzed. The grey correlation analysis method determines the weight according to the importance of each index, and transforms the multi-objective optimization problem into a single-objective optimization problem to improve the quality performance of the product[12]. In this experiment, the degree of correlation between the factors is judged according to the similarity or dissimilarity between the indicators, and the gray correlation analysis method is selected to optimize the injection molding process parameters.

Firstly, the signal-to-noise ratio is non-dimensionalized [13, 14]. After dimensionless, the data with different dimensions of each column can be converted into decimals between (0,1) to ensure the quality and reliability of the analysis. The calculation formula is:

$$y_i=\frac{max\eta_i-\eta_i}{max\eta_i-min\eta_i} \tag{2}$$

In formula (2): ηi is the signal-to-noise ratio value after the numerical transformation of the i th test; maxηi and minηi are the maximum and minimum values of the signal-to-noise ratio obtained from the experiment, respectively. yi is the dimensionless value of ηi.

The grey correlation coefficient is calculated. The grey correlation coefficient is the relationship between ideal data and dimensionless data. The calculation formula is:

$$\xi_i=\frac{min\left|y_i^0-y_i\right|+\rho\max\left|y_i^0-y_i\right|}{\left|y_i^0-y_i\right|+\rho\max\left|y_i^0-y_i\right|} \tag{3}$$

In formula (3): y0i is the i-th dimensionless ideal data, generally take 0 ; ρ is the resolution coefficient, generally 0.5.

The calculation formula of grey correlation degree is:

$$\gamma_i=\frac{1}{m}\sum_{i=1}^{m}\xi_i(i=1,2\cdots25) \tag{4}$$

In formula (4): m is the number of optimization objectives.

The volume shrinkage rate and X-direction deformation data obtained by orthogonal test are calculated according to Formula (1). The dimensionless calculation is carried out by Formula (2), and the grey correlation coefficient and grey correlation value are calculated according to Formula (3) and Formula (4)[15]. Table 7 shows the grey correlation coefficient and grey correlation degree of volume shrinkage and X-direction deformation.

Table 7. Grey correlation data of orthogonal test

Test number	Displacement deformation in X direction			Volume shrinkage			Grey correlation value
	Signal-to-noise ratio/dB	Non-dimensionalization	Grey incidence coefficient	Signal-to-noise ratio/dB	Non-dimensionalization	Grey incidence coefficient	
1	-6.918	0.207	0.707	-17.80	0.173	0.742	0.725
2	-6.756	0.192	0.722	-17.80	0.173	0.742	0.732
3	-6.658	0.183	0.732	-17.79	0.172	0.743	0.738
4	-6.500	0.173	0.743	-17.09	0.000	1.000	0.872
5	-6.366	0.000	1.000	-17.02	0.000	1.000	1.000
6	-7.411	0.402	0.554	-18.94	0.468	0.516	0.535
7	-7.186	0.357	0.583	-18.93	0.466	0.518	0.551
8	-6.918	0.207	0.707	-18.35	0.312	0.616	0.662
9	-6.658	0.183	0.732	-17.84	0.193	0.721	0.727
10	-7.550	0.441	0.531	-18.94	0.468	0.516	0.524
11	-7.664	0.469	0.516	-19.90	0.693	0.419	0.468
12	-7.474	0.422	0.542	-19.34	0.555	0.474	0.508
13	-9.028	1.000	0.333	-19.12	0.512	0.494	0.414
14	-7.957	0.584	0.461	-19.90	0.693	0.419	0.440
15	-7.708	0.480	0.510	-19.90	0.693	0.419	0.465
16	-7.776	0.497	0.501	-20.45	0.823	0.378	0.440
17	-7.784	0.499	0.500	-20.40	0.817	0.380	0.440
18	-8.132	0.634	0.441	-20.75	0.873	0.364	0.403
19	-8.050	0.607	0.452	-20.75	0.873	0.364	0.408
20	-7.796	0.504	0.498	-20.75	0.873	0.364	0.431
21	-7.912	0.557	0.473	-21.13	0.936	0.348	0.411
22	-8.266	0.713	0.412	-21.52	1.000	0.333	0.373
23	-8.262	0.712	0.413	-21.52	1.000	0.333	0.373
24	-8.208	0.689	0.421	-21.52	1.000	0.333	0.377
25	-8.088	0.631	0.442	-21.20	0.948	0.345	0.394

The range analysis of the grey correlation degree values corresponding to each group of tests is carried out. The larger the range is, the greater the influence of this factor on the grey correlation degree value is. Table 8 is the range analysis of grey correlation degree value, and figure 8 is the trend chart of factor level change.

Table 8. Grey correlation value range analysis

Project	Factor				
	Melt temperature	Mold temperature	Pressure duration	Packing pressure	Cooling time
M1	0.829 ℃	0.533 ℃	0.518 s	0.516 MPa	0.596 s
M2	0.623 ℃	0.588 ℃	0.566 s	0.551 MPa	0.584 s
M3	0.478 ℃	0.606 ℃	0.581 s	0.568 MPa	0.573 s
M4	0.412 ℃	0.621 ℃	0.594 s	0.592 MPa	0.562 s
M5	0.387 ℃	0.635 ℃	0.602 s	0.609 MPa	0.549 s
Extreme difference R	0.422 ℃	0.102 ℃	0.084 s	0.093 MPa	0.047 s

It can be seen from Table 8 and Figure 8 that the order of factors affecting the grey correlation degree is: melt temperature > mold temperature > holding pressure > holding time > cooling time. The optimal process parameter combination corresponding to the maximum range of grey correlation degree of each factor is A1B5C5D5E1, that is, the melt temperature is 190 °C, the mold temperature is 70 °C, the holding time is 12 s, the holding pressure is 37 MPa and the cooling time is 16 s.

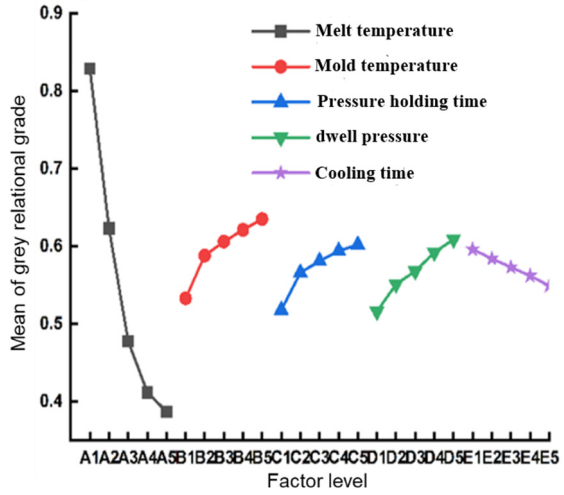


Fig 5. Change trend of factor level

5. Optimal Parameter Simulation Verification

The obtained optimal combination of process parameters is simulated in Moldflow software, and figure 9 is the optimized result of grey relational analysis. From Figure 9a and Figure 9b, it can be seen that the deformation value and volume shrinkage in the X direction have been reduced. Table 9 is the comparison of the results of the default parameter process combination, the optimal process combination of the orthogonal test and the optimal process combination of the gray correlation value. From table 9, it can be seen that the X-direction deformation under the optimal process combination of gray correlation value is 2.069 mm, which is 0.032 mm less than the X-direction deformation under the optimal process combination of orthogonal test deformation, and 0.343 mm less than the X-direction deformation under the default process parameter combination. The volume shrinkage of the plastic part is 6.872 %, which is 0.028 % lower than that under the optimal process combination of orthogonal test volume shrinkage, and 3.034 % lower than that under the default analysis process parameter combination. Therefore, the X-direction deformation and volume shrinkage under the optimization of grey correlation analysis have achieved relatively better results. Therefore, the combination of process parameters optimized by grey correlation analysis is suitable for the injection molding production of sweeping robot shell.

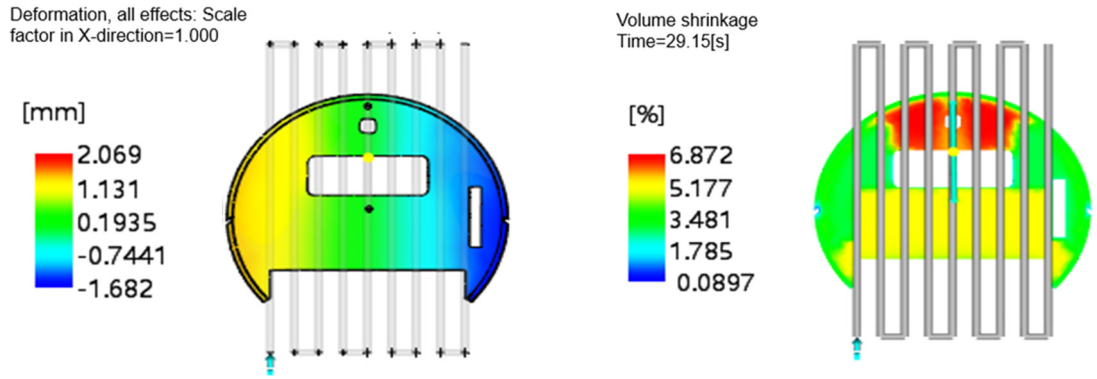


Fig 6. Optimization results of grey correlation analysis

6. Conclusion

In order to improve the forming quality of the sweeping robot shell, the warping deformation and volume shrinkage in the X direction were selected as the optimization objectives. The orthogonal test and Moldflow mold flow analysis software were used to carry out the L25 (55) orthogonal test. On the basis of the orthogonal test results, the signal-to-noise ratio and grey correlation analysis were used to optimize the forming process parameters. According to the range analysis of grey correlation degree, the influence degree of each process parameter on the grey correlation degree value and the optimal process parameter combination were obtained.

According to the verification and comparison of the optimal process parameter combination, it can be seen that the volume shrinkage and X-direction deformation obtained by the optimal process combination of gray correlation value have a certain degree of reduction. The X-direction deformation under the optimal process combination of the grey correlation degree value is 0.032 mm less than the X-direction deformation under the optimal process combination of the orthogonal test deformation, and 0.343 mm less than the X-direction deformation under the default process combination. The volume shrinkage rate under the optimal process combination of the grey correlation degree value is 0.028 % lower than that under the optimal process combination of the orthogonal test volume shrinkage rate, and 3.034 % lower than the volume shrinkage rate under the default process combination. In general, the grey correlation analysis optimization can obtain relatively better results. Under the orthogonal test, the optimal process parameter combination of volume shrinkage rate and the optimal process parameter combination of X-direction deformation are not the same. Therefore, it is difficult to obtain the minimum value of volume shrinkage rate and X-direction deformation at the same time. The multi-objective optimization can be transformed into single-objective optimization by grey correlation analysis, so as to improve the forming quality of the product.

Table 9. Comparison of process combination results

Project	Melt temperature	Mold temperature	Pressure duration	Packing pressure	Cooling time	Displacement deformation in X direction	Volume shrinkage
Default parameter	230 ℃	50 ℃	10 s	27 MPa	20 s	2.412 mm	9.906%
Orthogonal test X direction displacement optimal process parameters	190 ℃	40 ℃	11 s	32 MPa	16 s	2.101 mm	6.976%
Orthogonal test volume shrinkage optimal process parameters	190 ℃	60 ℃	12 s	37 MPa	16 s	2.111 mm	6.900%
The optimal process parameters of grey correlation value	190 ℃	70 ℃	12 s	37 MPa	16 s	2.069 mm	6.872%

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