Optimum Analysis of Microporous Foaming/Mould Decoration Compound Forming Technology for Automobile Door Decoration Panel

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Abstract. All Energy conservation and environmental protection are increasingly concerned by the automotive industry. Lightweight vehicles are one of the effective ways to achieve energy conservation and environmental protection. As an important method in plastic processing, the microcellular foam injection molding process can further meet the requirements of lightweight vehicles while meeting the performance requirements of the parts. However, a large number of bubbles exist on the surface of the microcellular foamed injection molded product, and the problems such as large surface roughness, low gloss, and poor apparent quality restrict the application of the process in automotive plastic parts. In order to improve the surface defects of microcellular foamed parts, this paper establishes experimental schemes and mathematical models based on partial factor test design method, response surface design and genetic algorithm, and obtains the optimal micro-foaming/in-mold decorative composite injection molding. Process parameter plan.

1. Introduction

Microcellular foam injection moulding plastic parts have shorter processing cycle and relatively stable size compared with traditional injection moulding plastic products, but there are crazes, whirlpool flow marks and bubble marks on the surface of microfoam plastic. Rough surface quality restricts the application prospects of this moulding technology in plastic parts [1].

The micro-foaming/in-mold decorative composite injection molding process has different thermal conductivity on both sides of the mold due to the intervention of the decorative film, which changes the flow characteristics of the gas/polymer mixed melt and the cell formation process, and improves the mechanics of the part. Performance and molding defects, so its process control is more complicated. Chen H Lobtained the following conclusions by studying the relationship between the composite film and the surface quality of microporous foamed products: The surface quality of products decreases with the increase of film thickness [3]. He Yongyuan studied the effect of temperature on warpage, shrinkage and residual stress by simulating and analyzing the process of microcellular foaming. According to rheological theory, the influence mechanism of process parameters was revealed [5].Hu Guanghong established the relationship among the three technological parameters in the process of Microcellular Foaming Injection moulding, i.e. cell nucleation rate, saturated melt pressure and melt temperature, and improved the mathematical model of bubble growth. The mathematical model was analyzed and validated by numerical calculation [6].

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In this paper, based on the partial factor test design method, the experimental scheme is established. The main influence parameters of the response model are melt temperature, mold temperature, V/P transition point and initial gas concentration. Based on the response surface design, the cell radius and warpage are respectively established. The prediction mathematical relationship model of tensile modulus; based on genetic algorithm to establish the process parameter optimization method under the defect minimization, the optimal process parameter scheme of micro-foaming/in-mold decorative composite injection molding is obtained.

2. Test Design

2.1. Modeling Analysis
The experiment selects the typical automobile trim-door trim panel as the research object, and builds the mold model diagram shown in Figure 1 according to the mold installation and design criteria. Using MOLDFLOW finite element software to simulate and analyze it, divide the grid and establish the gating system and cooling system. As shown in Figure 2, attach the decorative film to the outer surface of the door trim panel, and mesh and detect it. Establish a corresponding microcellular foaming/in-mold decorative composite injection molding system.

![Figure 1. Mould model diagram](image1)

![Figure 2. Finite element model](image2)

2.2. Material and Process Conditions
The experimental materials include polymer, decorative film and gas foaming agent. Polymers are PP composite materials, their viscosity properties and PVT properties are shown in Figure 3. TPU produced by Lubrizol manufacturer is selected for the film. Supercritical nitrogen (N2), critical pressure 3.4MPa, critical temperature - 147.05 C, gas constant R8.3145J/(mol k) and density 1.25kg/m3 were selected as blowing agent. The mould is manufactured by Generic manufacturer and the brand is TOOL STEEL P-20.

![Figure 3. Viscosity and PVT properties](image3)
In order to study the influence of the coupling effect between injection molding factors and factors on the forming properties, the analysis focuses on melt temperature, mold temperature, injection time, cooling temperature, V/P conversion point, initial gas concentration, number of gas cores per volume, and cooling. The influence of medium Reynolds number and cooling medium temperature on the composite forming process of automobile door trim.

2.3. Test

2.3.1. Partial Factor Test. In this section, melt temperature, mould temperature, injection time, cooling temperature, V/P conversion point, initial concentration of gas, number of gas nuclei per volume, Reynolds number of cooling medium and temperature of cooling medium are selected as initial factors. For the convenience of later elaboration, these eight factors are replaced by letters A, B, C, D, E, F, G, H respectively. The specific values of high and low levels are determined, as shown in Table 1. The experimental design of these eight factors is carried out and 16 groups of experimental arrays are obtained.

| number | factor                          | Code | Low level | High level |
|--------|---------------------------------|------|-----------|------------|
| 1      | Melt Temperature / °C           | A    | 200       | 240        |
| 2      | Mold temperature / °C           | B    | 40        | 60         |
| 3      | Injection time / s              | C    | 0.8       | 1.2        |
| 4      | V/P transformation point / %    | D    | 95 %      | 99 %       |
| 5      | Initial gas concentration / %   | E    | 0.3       | 0.7        |
| 6      | Number of gas nuclei per volume / m^3 | F | 1.8e+6 | 2.2e+6 |
| 7      | Reynolds number of coolant      | G    | 8000      | 12000      |
| 8      | Cooling medium temperature / °C | H    | 20        | 30         |

2.3.2. Response Surface Factor Test. Response Surface Methodology (RSM) can obtain the functional relationship between response and factor, so it has more advantages in optimum design. According to the results obtained from the experimental design of some factors, the main influencing factors are selected as follows: A (melt temperature), B (mould temperature), D (V/P conversion point), E (initial concentration of gas) as the research object, and the level is selected as shown in Table 2. The four process parameters that have no significant influence are as follows: injection time 0.8s, number of gas nuclei 2E+05 per volume, Reynolds number 10000 of cooling medium, temperature of cooling medium 25°C. After the process parameters except the main effect factor are set up in the same way, the central composite experiment is used to design the factors, and the response results of the central composite factor test array shown in Table 2 and extracted from MOLDFLOW model are obtained.

| number | factor                          | Low level | Medium level | High level |
|--------|---------------------------------|-----------|--------------|------------|
| A      | Melt Temperature / °C           | 200       | 220          | 240        |
| B      | Mold temperature / °C           | 40        | 50           | 60         |
| D      | V/P transformation point / %    | 95        | 97           | 99         |
| E      | Initial gas concentration / %   | 0.3       | 0.5          | 0.7        |
3. Results and Analysis

3.1. Analysis of Partial Factor Test

Three groups of results were obtained by MOLDFLOW simulation: cell radius (um), warpage result (mm) and tensile modulus (MPa), as shown in Table 3.

| number | A   | B   | C   | D   | E   | F   | G   | H   | Bubble radius(um) | Warpage results(mm) | Tensile modulus(MPa) |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-------------------|----------------------|----------------------|
| 1      | -1  | 1   | -1  | 1   | -1  | 1   | 1   | 1   | 7.36              | 10.03                | 874.76               |
| 2      | 1   | -1  | -1  | -1  | 1   | 1   | -1  | 1   | 5.32              | 9.86                 | 950.83               |
| 3      | 1   | 1   | -1  | -1  | -1  | -1  | -1  | 1   | 5.48              | 10.10                | 908.96               |
| 4      | -1  | -1  | 1   | -1  | -1  | -1  | 1   | 1   | 5.45              | 9.78                 | 990.71               |
| 5      | 1   | -1  | 1   | -1  | -1  | 1   | -1  | 1   | 8.52              | 9.78                 | 905.84               |
| 6      | -1  | -1  | -1  | 1   | -1  | -1  | 1   | 1   | 7.19              | 9.72                 | 974.48               |
| 7      | -1  | 1   | -1  | 1   | -1  | 1   | 1   | 1   | 5.19              | 10.31                | 942.72               |
| 8      | -1  | -1  | -1  | 1   | -1  | -1  | -1  | 1   | 5.1               | 9.99                 | 947.62               |
| 9      | -1  | 1   | 1   | 1   | -1  | -1  | 1   | 1   | 8.16              | 10.24                | 931.93               |
| 10     | -1  | 1   | -1  | 1   | 1   | -1  | 1   | 1   | 4.58              | 10.37                | 957.53               |
| 11     | -1  | -1  | 1   | -1  | 1   | 1   | 1   | 1   | 7.57              | 9.92                 | 906.90               |
| 12     | 1   | -1  | -1  | 1   | 1   | -1  | -1  | -1  | 8.28              | 9.88                 | 932.76               |
| 13     | 1   | 1   | -1  | 1   | -1  | 1   | -1  | -1  | 6.37              | 9.79                 | 859.61               |
| 14     | 1   | 1   | -1  | -1  | 1   | 1   | 1   | -1  | 7.63              | 9.69                 | 784.12               |
| 15     | -1  | 1   | 1   | 1   | -1  | 1   | 1   | 1   | 6.02              | 9.94                 | 962.64               |
| 16     | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 8.03              | 10.03                | 874.30               |

From Figure 4, it can be seen that the critical value for the influence of the radius of the bubble on the surface of the workpiece is 0.546, the critical value for the warpage result is 0.2139, and the critical value for the influence of the tensile modulus is 39.01. As shown by the dotted line in the Pareto diagram, the three factors that have significant influence on the radius of the bubble on the surface of the workpiece are the initial concentration of gas, the melt temperature and the injection time, in turn, which affect the warpage result. The most important factor is the temperature of the die. The notable factors affecting the tensile modulus are the temperature of the die, V/P conversion point, melt temperature and initial gas concentration.

Normal effect maps are used to screen the factors. Among these uncertain factors, the main factors which have obvious influence on the main effect are selected. As shown in Figure. 4, the significant factors are identified by red dots, which are gas initial concentration, melt temperature, injection time, mould temperature and V/P conversion point, while the other process parameters which have little influence on the results show blue.

![Figure 4. Paretochart (a) Bubble radius (b) Warpage (c) Tensile modulus](image-url)
Figure 5. Normal Effect Map (a) Bubble radius (b) Warpage (c) Tensile modulus

The Pareto plot is consistent with the significance of the influence factor screened by the normal effect diagram. According to the results obtained, the initial gas concentration, melt temperature, mold temperature and V/P transition point are selected as the research object.

3.2. Response Surface Analysis

Table 4. Central Composite Test Factor Array and Response Results

| number | A   | B   | D   | E   | Bubble radius(um) | Warpage results(mm) | Tensile modulus (MPa) |
|--------|-----|-----|-----|-----|-------------------|---------------------|-----------------------|
| 1      | 0   | 0   | 0   | -1  | 5.53              | 10.12               | 902.83                |
| 2      | 1   | 0   | 0   | 0   | 7.79              | 9.923               | 834.58                |
| 3      | 0   | 0   | 0   | 1   | 7.76              | 9.971               | 853.43                |
| 4      | 1   | -1  | 1   | -1  | 5.82              | 10.16               | 899.06                |
| 5      | -1  | 1   | -1  | -1  | 5.12              | 10.16               | 919.07                |
| 6      | 1   | 1   | 1   | 1   | 8.16              | 9.855               | 818.32                |
| 7      | -1  | 1   | -1  | 1   | 7.86              | 10.03               | 876.71                |
| 8      | -1  | 0   | 0   | 0   | 6.61              | 10.09               | 908.39                |
| 9      | 1   | -1  | -1  | 1   | 8.18              | 9.969               | 818.54                |
| 10     | 0   | -1  | 0   | 0   | 7.4               | 9.883               | 849.61                |
| 11     | -1  | -1  | -1  | -1  | 4.98              | 9.885               | 883.68                |
| 12     | -1  | -1  | 1   | 1   | 7.66              | 9.758               | 854.2                 |
| 13     | 0   | 0   | 0   | 0   | 7.06              | 10.04               | 879.21                |
| 14     | -1  | 1   | 1   | -1  | 5.12              | 10.16               | 936.91                |
| 15     | -1  | -1  | 1   | -1  | 4.98              | 9.864               | 903.34                |
| 16     | -1  | -1  | -1  | 1   | 7.66              | 9.783               | 832.4                 |
| 17     | 0   | 1   | 0   | 0   | 7.27              | 10.01               | 875.53                |
| 18     | 1   | 1   | 1   | -1  | 5.78              | 9.99                | 878.49                |
| 19     | 0   | 0   | 0   | 0   | 7.06              | 10.04               | 879.21                |
| 20     | 1   | 1   | -1  | -1  | 5.78              | 9.972               | 856.07                |
| 21     | 1   | 1   | -1  | 1   | 8.16              | 9.854               | 796.34                |
| 22     | 0   | 0   | 0   | 0   | 7.06              | 10.04               | 879.21                |
| 23     | 0   | 0   | 1   | 0   | 7.06              | 10.06               | 892.3                 |
| 24     | 0   | 0   | -1  | 0   | 7.06              | 10.03               | 867.65                |
| 25     | 0   | 0   | 0   | 0   | 7.06              | 10.04               | 879.21                |
| 26     | 0   | 0   | 0   | 0   | 7.06              | 10.04               | 879.21                |
| 27     | 1   | -1  | 1   | 1   | 8.18              | 10                 | 844.54                |
| 28     | -1  | 1   | 1   | 1   | 7.86              | 10.05               | 901.09                |
| 29     | 0   | 0   | 0   | 0   | 7.06              | 10.04               | 879.21                |
| 30     | 0   | 0   | 0   | 0   | 7.06              | 10.04               | 879.21                |
| 31     | 1   | -1  | -1  | -1  | 5.82              | 10.12               | 876.57                |
The central composite experiment was used to design the factors. The experimental array of the central composite experiment factors shown in Table 4 and the response results extracted from the MOLDFLOW model were obtained.

![Factor Interaction Surface Diagram](image)

**Figure 6. Factor Interaction Surface Diagram**

Figure 6 shows that the interaction between the V/P transition point and the initial gas concentration is small. When the V/P transition point is at a different level, the bubble radius decreases with the initial concentration of the gas, i.e., at V/ A smaller initial gas concentration is used to reduce the radius of the cell when the P-switching point is at different levels.

![Factor Interaction Surface Diagram](image)

**Figure 7. Factor Interaction Surface Diagram**
3.3. Defect Prediction and Process Optimization

It can be seen from the normal probability map of the defect shown in Fig. 8 that the residual between the experimental value of the cell radius, warpage and tensile modulus and the fitted value are distributed near the standard oblique line, indicating that the residual obeys the normal state. Distribution; the defect and the fitted value map are as shown in Fig. 9, and the residual value is kept equal to the variance; as shown in Fig. 10, the residual values are not regularly distributed on the horizontal axis; the cell radius and warpage are explained. The mathematical prediction model of tensile modulus is highly accurate.

Figure 8. Normal probability diagram

Figure 9. And fitting value

Figure 10. And sequence diagram
Therefore, the mathematical regression equation of bubble radius is:

\[ Y_i = 7.1067 + 0.3233A + 0.0239B + 1.2528E + 0.0388A^2 + 0.1738B^2 - 0.1012D^2 - 0.5162E^2 - 0.0500AB - 0.0850AE + 0.0100BE \]  

\[ (1) \]  

The mathematical regression equation of warpage results is:

\[ Y_2 = 10.0333 + 0.00350A + 0.03661B + 0.00522D - 0.06450E - 0.0190A^2 - 0.0790B^2 + 0.0195D^2 + 0.0200E^2 - 0.10550AB + 0.00725AD - 0.00725AE + 0.00088BD + 0.00163BE - 0.00063DE \]  

\[ (2) \]  

The regression equation of tensile modulus is:

\[ Y_3 = 877.43 - 21.85A + 5.37B + 11.18D - 25.58E - 3.86A^2 - 12.78B^2 + 4.63D^2 + 2.78E^2 - 15.60AB + 0.58AD - 3.37AE - 0.21BD + 0.93BE + 0.73DE \]  

\[ (3) \]  

\[ F(x) = \frac{Y_i^2 + Y_2^2}{Y_3^2} \]  

\[ (4) \]  

S.T. \(-1 \leq x_i \leq 1;\)  

In the formula, \( F(x) \) represents the optimal result obtained by fitting.  

The GA genetic algorithm toolbox is used to iteratively calculate the function, and the four process parameters A, B, D, and E are optimized. When the optimization target result is 0.134487, the four parameters are combined \((-1, -0.221, 1), (-1, -0.221, 1),\) the melt temperature after fitting was 200 ° C, the mold temperature was 47.79 ° C, the V/P conversion point was 99%, and the initial gas concentration was 0.3%.  

In order to test the optimization results of the genetic algorithm, the optimized process parameters were substituted into Moldflow to obtain a cell radius of 4.7 um, a warpage result of 10.17 mm, and a
tensile modulus of 938.09 MPa, which was 0.1338, which met the accuracy requirement. Then, when the melt temperature is 200 °C, the mold temperature is 47.79 °C, the injection time is 1 s, the V/P conversion point is 99%, the initial gas concentration is 0.3%, the number of gas cores per volume is 2E+05, the Reynolds number of the cooling medium is 10000, and the temperature of the cooling medium is 25 °C, it helps to obtain the best part quality.

4. Conclusion

(1) According to the partial factor test design, the three factors that have significant influence on the cell surface radius are the initial gas concentration, melt temperature and injection time. The most influential factor on the warpage result is the mold temperature and pull. The significant factors affecting the modulus of elongation are mold temperature, V/P transition point, melt temperature, and initial gas concentration. The accuracy between the model and the experimental values was verified by a central composite test design.

(2) Using genetic algorithm analysis, the optimal combination of process parameters was obtained, that is, when the melt temperature was 200 °C, the mold temperature was 47.79 °C, the injection time was 1 s, the V/P conversion point was 99%, the initial gas concentration was 0.3%, and the number of gas cores per volume was 2E+05, the Reynolds number of the cooling medium is 10000, and the temperature of the cooling medium is 25 °C, which helps to obtain the best quality parts.

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