Injection Molding Process Optimization of Polypropylene using Orthogonal Experiment Method Based on Tensile Strength

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Abstract. The process parameters have direct influence on the performance and quality of final products of polypropylene (PP) in injection molding. In order to optimize injection molding process of PP and obtain expected tensile strength, tensile tests designed according to orthogonal experiment method of 7 factors at 3 levels were carried out on the injection molding machine, and relevant data were analyzed by range analysis method. The results show that, in the scope of given experiment, the process parameters affecting tensile strength of PP from high to low are injection pressure, melt temperature, cooling time, packing time, packing pressure, mold temperature and injection rate, and the optimal values of injection molding process parameters are melt temperature 200°C, injection pressure 5 MPa, injection rate 200 mm·s⁻¹, packing pressure 3 MPa, packing time 40 s, cooling time 40 s and mold temperature 40°C, which is further verified by additional test.

1. Introduction

Owing to the excellence of abundance in raw material, low price, excellent mechanical properties, polypropylene (PP) has been applied widely in automobile, home appliance and machinery [1]. With the rapid expanding of applied range of PP and its products, a higher demand for visual quality and performance is proposed accordingly. Therefore, how to control the molding quality of PP products has become one of the key issues in the field of PP application.

The injection molding, as being the most widely used molding method in plastics for the advantages of high production efficiency and strong processing adaptation, is a multivariable, nonlinear and periodic unsteady process [2]. After the determining of raw materials, injection molding machine and die structure, the key factor that decides the quality of molding products is the selection of the injection molding process parameters which can be carried out traditionally by trial and error according to expertise and practical experience of experts. It’s difficult and expensive to optimize the injection molding process parameters and obtain high-quality products accordingly by trial and error, although it has been used for many years [3]. The orthogonal experiment method can reduce in part the blindness in trial and error, and obtain optimal scheme of concerned parameters [4, 5]. In this research, taking tensile strength of PP as decision standard of quality, we will study the significance extent of the
injection molding process parameters on the quality of PP specimen using orthogonal experiment and range analysis method, and present optimal process parameters in the scope of experiment accordingly. All the above are helpful for injection molding and academic research of PP.

2. Experiments

2.1. Injection molding
The tensile specimens were prepared by granular PP (S800, supplied by Gansu Langang Petrochemical Co. Ltd.) through a Concept 80/420-200 injection molding machine under a certain process parameters.

2.2. Tensile strength test
The tensile strength of PP specimen was tested with a tensile rate of 50 mm/min by a WSM20KN tensile testing machine (manufactured by Changchun Intelligent Instrument & Equipment Co. Ltd.) according to GB/T1040.1-2006. Five specimens were tested in each molding process, and the average value was taken.

2.3. Selection of injection molding process parameters
As mentioned in introduction, the influence law of injection molding process parameters on the quality of PP and its products is quite complicated. In order to analyze the influence of process parameters on tensile strength quantitatively, melt temperature (A), injection pressure (B), injection rate (C), packing pressure (D), packing time (E), cooling time (F) and mold temperature (G) were selected as main process parameters in this research according to injection molding machine used.

2.4. The orthogonal experiment design
The orthogonal experiment method can analyze the significance extent and law of process parameters to tensile strength of PP with fewer tests, and optimize process parameters of injection molding accordingly. The influences of process parameters on tensile strength of PP were researched by an orthogonal experiment of 7 factors at 3 levels, as shown in Tab. 1. Accordingly, the orthogonal experiment design L18 (3^7) was given in Tab. 2.

| Levels | Factors |
|--------|---------|
|        | A /°C   | B /MPa | C /mm·s⁻¹ | D /MPa | E /s | F /s | G /°C |
| 1      | 180     | 3      | 180       | 3      | 20  | 30  | 20   |
| 2      | 200     | 5      | 200       | 5      | 30  | 40  | 40   |
| 3      | 220     | 7      | 220       | 7      | 40  | 50  | 60   |

3. Results and discussion

3.1. Significance extent analysis of process parameters
The tensile strength (σ) of PP corresponding to orthogonal experiment array is also given in Tab. 2. The influences of injection molding process parameters on tensile strength can be analyzed by range analysis method using formulas (1) and (2).

$$k_i = K_i/s$$  \hspace{1cm} (1)

$$R = max \{k1, k2, k3\} - min \{k1, k2, k3\}$$  \hspace{1cm} (2)

Where $K_i$ is the sum of tensile strength of some factor at level $i$, $k_i$ is arithmetic mean of tensile strength of some factor at level $i$, $s$ is the number of occurrences of some factor at each level, and $R$ is range. The results obtained by range analysis method are shown in Tab. 3.
The value of $R$ represents the significance extent of some factor on tensile strength. The larger the value, the more the significance is. Therefore, it can be seen from Tab. 3, the process parameters affecting tensile strength from high to low are injection pressure, melt temperature, cooling time, packing time, packing pressure, mold temperature and injection rate.

Table 2. Experiment array and test results.

| Test number | A /°C | B /MPa | C /mm·s$^{-1}$ | D /MPa | E /s | F /s | G /°C | σ /MPa |
|-------------|-------|--------|----------------|--------|------|------|-------|--------|
| 1           | 1     | 1      | 1              | 1      | 1    | 1    | 1     | 28.08  |
| 2           | 1     | 2      | 2              | 2      | 2    | 2    | 2     | 31.17  |
| 3           | 1     | 3      | 3              | 3      | 3    | 3    | 3     | 27.42  |
| 4           | 2     | 1      | 1              | 2      | 2    | 3    | 3     | 30.72  |
| 5           | 2     | 2      | 2              | 3      | 3    | 1    | 1     | 32.10  |
| 6           | 2     | 3      | 3              | 1      | 1    | 2    | 2     | 30.28  |
| 7           | 3     | 1      | 2              | 1      | 3    | 2    | 3     | 31.02  |
| 8           | 3     | 2      | 3              | 2      | 1    | 3    | 1     | 30.98  |
| 9           | 3     | 3      | 3              | 1      | 3    | 2    | 1     | 27.99  |
| 10          | 1     | 1      | 3              | 3      | 2    | 2    | 2     | 29.01  |
| 11          | 1     | 2      | 1              | 1      | 3    | 3    | 2     | 31.31  |
| 12          | 1     | 3      | 2              | 2      | 1    | 1    | 3     | 27.42  |
| 13          | 2     | 1      | 2              | 3      | 1    | 3    | 2     | 30.05  |
| 14          | 2     | 2      | 3              | 1      | 2    | 1    | 3     | 32.34  |
| 15          | 2     | 3      | 1              | 2      | 3    | 2    | 1     | 30.18  |
| 16          | 3     | 1      | 3              | 2      | 3    | 2    | 2     | 30.36  |
| 17          | 3     | 2      | 1              | 3      | 3    | 1    | 3     | 31.18  |
| 18          | 3     | 3      | 2              | 1      | 2    | 1    | 1     | 28.66  |

Table 3. Range analysis of factors and levels.

| A/°C | B/MPa | C/mm·s$^{-1}$ | D/MPa | E/s | F/s | G/°C | $K_1$ | $K_2$ | $K_3$ | $k_1$ | $k_2$ | $k_3$ | $R$ |
|------|-------|--------------|-------|-----|-----|------|-------|-------|-------|-------|-------|-------|-----|
| 174.41 | 179.24 | 179.46 | 181.69 | 177.99 | 176.59 | 179.01 | 185.67 | 189.08 | 180.42 | 180.83 | 179.89 | 182.02 | 181.16 |
| 180.19 | 171.95 | 180.39 | 177.75 | 182.39 | 181.66 | 180.10 | 29.07 | 29.87 | 29.91 | 30.28 | 29.67 | 29.43 | 29.84 |
| 30.03 | 28.66 | 30.07 | 29.63 | 30.40 | 30.28 | 30.02 | 1.88 | 2.85 | 0.16 | 0.65 | 0.73 | 0.91 | 0.35 |

The melt temperature affects both molding process and product quality directly. More specifically, excessive melt temperature will lead to the degradation of PP, causing the decline of mechanical properties dramatically. While appropriately increasing the melt temperature will be favorable to reduce the melt viscosity, decrease the pressure of injection system, increase melt flow rate and injection rate, shrink injection period [6]. But for the current molding process, the significance extent of melt temperature, located at the second place, is lower than that of injection pressure. The influence of packing pressure on tensile strength is somewhat complicated. By interacting with each other, packing pressure and other process parameters form an entirety and affect tensile strength together.

Fig. 1 shows also the influence of each factor on tensile strength from variation range of $k_i$ obtained by Tab. 3. Obviously, the solution is consistent with the analysis of range $R$. The greatest influence factor is B (injection pressure), followed by A (melt temperature).
3.2. Optimization of process

For some factor, the larger the $k_i$ is, the better the level $i$ is. Therefore, the optimal scheme of factor and level is $A_2B_2C_2D_1E_3F_2G_2$ according to Fig. 1. Of course, this solution can also be obtained from Tab. 3. Accordingly, the optimal values of injection molding process parameters of PP are melt temperature being 200 °C, injection pressure 5 MPa, injection rate 200 mm·s$^{-1}$, packing pressure 3 MPa, packing time 40 s, cooling time 40 s and mold temperature 40°C.

3.3. Verification of optimal of process

Compared with Tab. 2, it can be seen that the optimal scheme of injection molding process has not been tested. And it is needed to carry out additional test. The tensile strength obtained by additional test is 33.57 MPa which is higher than that existed. This indicates, from the point of experiment, the injection molding process obtained is exactly optimal.

4. Conclusion

Referring to the optimization of injection molding process of PP, taking tensile strength as decision standard of quality, orthogonal experiment of 7 factors at 3 levels was designed, and the experiment results were analyzed by range analysis method. The following solutions were obtained accordingly.

The injection molding process parameters affecting tensile strength of PP in a descending order are injection pressure, melt temperature, cooling time, packing time, packing pressure, mold temperature and injection rate.

The optimal injection molding process in the scope of experiment are melt temperature being 200°C, injection pressure 5 MPa, injection rate 200 mm·s$^{-1}$, packing pressure 3 MPa, packing time 40 s, cooling time 40 s and mold temperature 40°C. And the tensile strength obtained by additional test indicates the optimization is scientific and reasonable.

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