Influence of gas counter pressure injection molding parameters on shrinkage ratio of plastic part

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Abstract: Gas counter pressure (GCP) technology can increase the pressure of melt before flowing effectively. Therefore, it has a potential to reduce shrinkage ratio and improve dimensional accuracy of conventional injection molding part. The effect of different process parameters on the shrinkage ratio of molded parts was studied by means of S/N ratio and ANOVA. The results showed that GCP pressure was the most important factor affecting the shrinkage ratio of molded parts, followed by packing time, injection pressure, mold temperature, melt temperature and packing pressure. Meanwhile, the most optimal combination of process parameters and 1.27% shrinkage ratio of parts were obtained. Finally, the influence of different process parameters on the shrinkage ratio of molded parts was also analyzed.

1. Introduction
Due to its various advantages including high level of automation, short molding cycle, wide molding material, injection molding technology has been widely used in many fields, such as electronic products, daily appliances, automobile, and so on.[1-3] With the development of plastic processing industry, many novel injection molding processes have been proposed, such as rapid mold heating and cooling [4, 5], foaming injection molding [6], gas-assisted injection molding [7-9], micro-injection molding [10, 11].

In conventional injection molding (CIM) process, macromolecule melt mainly undergoes high temperature melting, shear flow and cooling solidification. The defects of shrinkage and warpage deformation appear easily for CIM parts. They greatly reduce the quality of the product.

For now, many researches have been investigated for improving the dimension accuracy of CIM parts. Muhammad et al.[12] studied the effects of different processing parameters on shrinkage and warpage of PP-nano clay injection molded parts by orthogonal experimental design. Hakimian et al.[13] studied the warpage and shrinkage deformation of CIM micro gears. The results showed that fiber glass percentage in polymer matrix has more significant effects on warpage and shrinkage. Rahimi et al.[14] investigated the effect of reprocessing process on shrinkage and mechanical properties of molded samples. The results showed that, with the increase of reprocessing cycles, the shrinkage of samples are reduced.

Azaman et al.[15] investigated the effect of different parameters on volumetric shrinkage and warpage deformation of a thin-walled plastic part. Comparing to cooling time and packing time, mold temperature and packing pressure have more significant effects on shrinkage and warpage.

By using the method of orthogonal numerical simulation experiments, Mathivanan et al.[16] studied the effect of different parameters on sink mark depth of a disk part. Kitayama et al.[17] investigated the effect of different parameters on shrinkage and clamping force of molded part by...
using sequential approximate optimization (SAO) method. They found high injection pressure and packing pressure will reduce volume shrinkage of molded part. By using methods of Taguchi and ANOVA, Altan et al. [18] studied the effect of different molding parameters on shrinkage of molded parts. They found that the most important process parameter affecting molded PP part is packing pressure.

Barghash et al. [19] investigated the effect of different parameters on shrinkage and warpage of plastic parts. It comes to the conclusion that prolonging of injection time and packing time will decrease dimensional shrinkage of molded parts.

Researchers have studied a diversity of methods to reduce the shrinkage ratio of molded parts, such as process parameters optimization [20, 21], advanced injection molding process [22], novel mold structure. There is no doubt that above mentioned defective control methods improved dimensional accuracy of CIM parts to a certain extent. However, recent researches have suggested that the CIM parts still have a relatively large shrinkage.

Insufficient pressurizing of injection system to melt flow front is also a main reason causing large shrinkage ratio of CIM parts. Based on above ideas, GCP technology was applied in the CIM process, meanwhile, the effects of GCP process on melt filling process, shrinkage and mechanical properties of CIM sample were studied. [23] It is found that GCP technology can effectively reducing the shrinkage of CIM parts.

Because of the great amount of control parameters in GCP assisted CIM process, the control process becomes more difficult. For now, there are relatively few researches of reducing shrinkage ratio of molded parts by using GCP technology. Meanwhile, there still not exist enough related investigation reports which involve the effect of GCP assisted CIM process parameters on shrinkage ratio of molded part. In order to study effect of GCP assisted CIM process parameters on shrinkage ratio of molded parts, the standard stretch spline was chosen as the research object. GCP assisted CIM experiments were performed. The effect of mold temperature, melt temperature, injection pressure, packing pressure, packing time and GCP pressure, on shrinkage ratio of molded part was studied by using S/N ratio and ANOVA. Finally, the effect mechanism of mold temperature, melt temperature, injection pressure, packing pressure, packing time and GCP pressure on shrinkage ratio of molded part was discussed and analyzed.

2. Experimental design

2.1 Material and equipment

PP (7000-NR700) manufactured by WOTE ADVANCED MATERIALS Ltd. was chosen for the material of plastic part. The shrinkage ratio of PP was 1.6~1.8%. The material was dried 10 hours at 80°C.

GCP assisted CIM system is shown as Figure 1. High pressure nitrogen was used for mold cavity pressurizing. GCP pressure and GCP holding time are controlled by GCP control equipment.

![Figure 1. GCP assisted CIM system](image)

2.2 Orthogonal experimental design

Six process parameters, including mold temperature, melt temperature, injection pressure, packing
pressure, packing time and GCP pressure were selected to investigate influence mechanism of different GCP injection molding parameters on shrinkage ratio of CIM part. The levels of different parameters were selected according to actual production experience. The value levels of molding parameters were listed in Table 1. Other parameters were set as: cooling time 60s, hot runner temperature 200°C, GCP holding time equal to packing time.

Table 1. Parameters and levels used for GCP assisted CIM process

| Parameter             | Level 1 | Level 2 | Level 3 |
|-----------------------|---------|---------|---------|
| Mold temperature (°C) | 30      | 50      | 70      |
| Melt temperature (°C) | 200     | 210     | 220     |
| Injection pressure (MPa) | 60    | 70      | 80      |
| Packing pressure (MPa) | 40     | 50      | 60      |
| Packing time (s)      | 5       | 10      | 15      |
| GCP pressure (MPa)    | 2       | 5       | 8       |

Table 2 is the orthogonal array L18 (3^6) of six factors and three levels, where A, B, C, D, E and F represent mold temperature, melt temperature, injection pressure, packing pressure, packing time and GCP pressure, respectively. GCP assisted CIM molding processes were carried to molding standard stretch samples (ASTM: D638) according above orthogonal experimental design. Sizes of molded samples were measured after 120 hours, and shrinkage ratio of each samples were measured.

For each condition, measure shrinkage ratio of five samples, and calculate average value as the shrinkage ratio of sample. Shrinkage ratio of samples can be calculated by following formula.

\[
\alpha = \frac{L - L_0}{L} \times 100\%
\]

where \( \alpha \) is the shrinkage of sample; \( L \) is the designed length of sample; \( L_0 \) is the actually length of molded sample.

Table 2. Orthogonal array L18 (3^6) used for GCP assisted CIM experiment

| No. | A | B | C | D | E | F | \( \alpha \) (%) | S/N |
|-----|---|---|---|---|---|---|-----------------|-----|
| 1   | 1 | 1 | 1 | 1 | 1 | 1 | 1.59           | -4.01|
| 2   | 1 | 2 | 2 | 2 | 2 | 2 | 1.39           | -2.85|
| 3   | 1 | 3 | 3 | 3 | 3 | 3 | 1.33           | -2.48|
| 4   | 2 | 1 | 1 | 2 | 2 | 3 | 1.37           | -2.77|
| 5   | 2 | 2 | 2 | 3 | 3 | 1 | 1.43           | -3.08|
| 6   | 2 | 3 | 3 | 1 | 1 | 2 | 1.34           | -2.52|
| 7   | 3 | 1 | 2 | 1 | 3 | 2 | 1.37           | -2.73|
| 8   | 3 | 2 | 3 | 2 | 1 | 3 | 1.41           | -3.00|
| 9   | 3 | 3 | 1 | 3 | 2 | 1 | 1.56           | -3.84|
| 10  | 1 | 1 | 3 | 3 | 2 | 2 | 1.39           | -2.85|
| 11  | 1 | 2 | 1 | 1 | 3 | 3 | 1.37           | -2.73|
| 12  | 1 | 3 | 2 | 2 | 1 | 1 | 1.52           | -3.66|
| 13  | 2 | 1 | 2 | 3 | 1 | 3 | 1.41           | -2.95|
| 14  | 2 | 2 | 3 | 1 | 2 | 1 | 1.52           | -3.61|
| 15  | 2 | 3 | 1 | 2 | 3 | 2 | 1.32           | -2.43|
| 16  | 3 | 1 | 3 | 2 | 3 | 1 | 1.51           | -3.58|
| 17  | 3 | 2 | 1 | 3 | 1 | 2 | 1.53           | -3.70|
| 18  | 3 | 3 | 2 | 1 | 2 | 3 | 1.30           | -2.30|

2.3 S/N ratio analysis
For the GCP assisted CIM part, a smaller shrinkage ratio means a higher quality of molded part. The purpose of this research is to decrease shrinkage ratio of the GCP assisted CIM part. So, the “smaller-the-better” S/N ratio was appropriate. The S/N ratio can be calculated by following formula.

\[ \eta = -10\log(MSD) \]  

(1)

where \( \eta \) represents S/N ratio, \( MSD \) is the mean-square deviation for the output characteristic. The calculation formula of \( MSD \) is defined as follows.

\[ MSD = \frac{1}{N} \left[ \sum_{i=1}^{N} Y_i^2 \right] \]  

(2)

where \( Y_i \) denotes the shrinkage ratio of molded part in the \( i \)th test, \( N \) is the total number of test.

For each experiment condition, S/N ratio was calculated by formula (1) and formula (2), listed in Table 2. S/N ratio and maximum difference of different level of each parameter were calculated, the calculated results were shown in Table 3.

Table 3. S/N ratio and maximum difference of different level of each molding parameter

| Factor | Level 1 | Level 2 | Level 3 | Max difference |
|--------|---------|---------|---------|---------------|
| A      | -3.10   | -2.89   | -3.19   | 0.30          |
| B      | -3.15   | -3.16   | -2.87   | 0.29          |
| C      | -3.25   | -2.93   | -3.01   | 0.32          |
| D      | -2.98   | -3.05   | -3.15   | 0.17          |
| E      | -3.31   | -3.04   | -2.84   | 0.47          |
| F      | -3.63   | -2.85   | -2.70   | 0.93          |

According to the data in Table 3, the relationship curves between S/N ratio and shrinkage ratio were drawn, and the results were shown in Figure 2. It can be found that \( A_2B_3C_2D_1E_3F_3 \) is the optimal process combination, which means: mold temperature 50℃, melt temperature 220℃, injection pressure 70MPa, packing pressure 40MPa, packing time 15s, GCP pressure 8MPa.

Figure 2. Relation curves between process parameter levels and signal to noise ratio

Since the optimal process combination was not included in the orthogonal experimental design, it is necessary to predict the minimum shrinkage ratio and conduct corresponding test to validate it. S/N ratio of \( A_2B_3C_2D_1E_3F_3 \) was calculated firstly by follows.

\[ \eta_{\text{optimal}} = \eta_{A_2} + \eta_{B_3} + \eta_{C_2} + \eta_{D_1} + \eta_{E_3} + \eta_{F_3} - 5\eta_{\text{average}} \]
\[
\begin{align*}
= (-2.89) + (-2.87) + (-2.93) + (-2.98) + (-2.84) + (-2.70) - 5 \times (-3.06) \\
= -1.91
\end{align*}
\]

The calculated S/N ratio of \(A_2B_3C_2D_1E_3F_3\), \(\eta_{optimal}\), is larger than other combinations of parameters. By substituting \(\eta_{optimal}\) into equation (1) and (2), the value of shrinkage ratio of the GCP assisted CIM part can be calculated as 1.25%.

To verify the accuracy of the prediction of shrinkage ratio, the injection experiment was conducted by using the optimal parameter combination of mold temperature 50°C, melt temperature 220°C, injection pressure 70MPa, packing pressure 40MPa, packing time 15s, and GCP pressure 8MPa. The obtained shrinkage ratio of molded part is 1.27%. The relative deviation between predicted value and actual value is only 1.57%.

| A (℃) | B (℃) | C (MPa) | D (MPa) | E (s) | F (MPa) | Predicted \(\alpha\) (%) | Actual \(\alpha\) (%) | Deviation (%) |
|------|------|--------|--------|------|-------|----------------|----------------|--------------|
| 50   | 220  | 70     | 40     | 15   | 8     | 1.25           | 1.27           | 1.57         |

\subsection*{2.4 ANOVA}

ANOVA method was utilized to quantitatively analyze the statistical significance of each parameter to shrinkage ratio, and relative results are listed in Table 5. Specific calculation steps are as follows.

\textbf{Sum of squares}

Total sum of squares of shrinkage ratio, \(SS_{Total}\), can be obtained by follows.

\[
SS_{Total} = \sum_{i=1}^{N} (d_i - \bar{d})^2
\]

(3)

where \(d_i\) is the shrinkage ratio of GCP assisted CIM part molded at the \(i\)th test, \(\bar{d}\) is the average value of shrinkage ratio of all test conditions, \(N\) is the number of all experiments.

For factor A, the \(SS_A\) can be calculated using the following formula.

\[
SS_A = \frac{1}{k} \sum_{m=1}^{k} \left( \frac{1}{v} \sum_{n=1}^{v} d_{mn} \right)^2 - \frac{1}{N} \left( \sum_{i=1}^{N} d_i \right)^2
\]

(4)

where \(k\) is the number of levels of parameter A, \(v\) is the number of experiments corresponding to each level of parameter A, \(d_{mn}\) is the shrinkage ratio in the \(n\)th experiment corresponding to parameter A at \(m\)th level.

For other parameters, \(SS_B\), \(SS_C\), \(SS_D\), \(SS_E\) and \(SS_F\) can be obtained in the same way. Finally, the residual sum of squares, \(SS_{Error}\), can be calculated.

\[
SS_{Error} = SS_{Total} - SS_A - SS_B - SS_C - SS_D - SS_E - SS_F
\]

(5)

\textbf{Degree of freedom}

The total degree of freedom can be calculated as follows.

\[
df_{Total} = N - 1
\]

(6)

For parameter A,

\[
df_A = k - 1
\]

(7)

For other parameters, \(df_B\), \(df_C\), \(df_D\), \(df_E\) and \(df_F\) can be obtained in the similar way.

The degree of freedom of the residual sum of squares, \(df_{Error}\), can be obtained using the following formula.

\[
df_{Error} = df_{Total} - df_A - df_B - df_C - df_D - df_E - df_F
\]

(8)
Mean square
For parameter A, mean square is obtained by follows

\[ MS_A = \frac{SS_A}{df_A} \] (9)

In the similarly way, \( MS_B, MS_C, MS_D, MS_E, MS_F \), can be calculated respectively.

Finally, \( MS_{\text{Error}} \), can be calculated.

\[ MS_{\text{Error}} = \frac{SS_{\text{Error}}}{df_{\text{Error}}} \] (10)

F-ratio
For parameter A, \( F_A \), is calculated by following formula:

\[ F_A = \frac{MS_A}{MS_{\text{Error}}} \] (11)

For other parameters, \( F_B, F_C, F_D, F_E \) and \( F_F \) can be obtained respectively.

Percentage contribution
Percentage contribution of parameter A, \( P_A \), is

\[ P_A = \frac{SS_A}{SS_{\text{Total}}} \] (12)

For other parameters, \( P_B, P_C, P_D, P_E \) and \( P_F \) can be obtained in the same way.

Table 5. ANOVA results of shrinkage ratio of GCP assisted CIM samples

| Item | SS   | df | MS  | F    | P (%) |
|------|------|----|-----|------|-------|
| A    | 0.0080 | 2 | 0.0040 | 3.60 | 5.921 |
| B    | 0.0079 | 2 | 0.0040 | 3.60 | 5.918 |
| C    | 0.0097 | 2 | 0.0049 | 4.41 | 7.260 |
| D    | 0.0021 | 2 | 0.0011 | 0.95 | 1.569 |
| E    | 0.0188 | 2 | 0.0094 | 8.50 | 13.985|
| F    | 0.0822 | 2 | 0.0411 | 37.20| 61.232|
| Error| 0.01  | 5 | 0.0011 | 4.115|       |
| Total| 0.13  | 17|      |      | 100   |

Table 5 shows that the order of contribution sequence is GCP pressure, packing time, injection pressure, mold temperature, melt temperature and packing pressure, meanwhile, corresponding contribution percentages are 61.232%, 13.985%, 7.260%, 5.921%, 5.918% and 1.569%, respectively.

3. Results and discussions
This paper systematically investigated the effect of GCP assisted CIM parameters on shrinkage ratio of CIM part. From the above research results, it can be found that the most significant parameter for shrinkage ratio of molded part is GCP pressure, which contributes 61.232% to the total. High GCP pressure will reduce the shrinkage ratio of molded part. In the process of GCP assisted CIM, a bi-directional compression action to melt can be formed between GCP pressure and injection nozzle, making macromolecule melt more compact, which means the shrinkage ratio of molded part after complete cooling small. The larger the GCP pressure is, the more compact the melt polymer molecular arrangement is, the smaller shrinkage ratio of samples after cooling is.

Packing time is the second important factor affecting shrinkage ratio of molded part, which contributes 13.985% to the total. With the increase of packing time, shrinkage ratio of molded part decreases. With or without packing process at the point of the gate completely cooling time directly affects shrinkage ratio of molded part. If the packing process is completed before the gate cooling, no more melt enters the mold cavity in the later stages of the cooling process, then the shrinkage ratio of
molded part is large. If the packing process is completed after the gate cooling, enough melt enters the mold cavity in whole stages of the cooling process, then the shrinkage ratio of molded part becomes small.

The third important parameter affecting shrinkage ratio of GCP assisted CIM part is injection pressure, which contributes 7.260% to the total. With the increased injection pressure, the shrinkage ratio of molded part presents a trend of firstly decreasing and then increasing. In GCP assisted CIM process, increasing injection pressure can shorten the filling time of the melt, and can ensure enough melt at the end of melt flow, which reduces the shrinkage ratio of molded part to some extent. While excessive injection pressure increases shear action of mold cavity on melt during filling process. Thus, excessive injection pressure causes to larger orientation of molecular chain. The rebound of the molecular chain is larger in cooling process after ejection process. The shrinkage ratio of molding part is larger.

The fourth important parameter affecting shrinkage ratio of molded part is mold temperature, which contributes 5.921% to the total. With the increased melt temperature, the shrinkage ratio of molded part shows a tendency of firstly decreasing and then increasing. Increasing mold temperature is conducive to the improvement of melt filling and replication capacity, which will reduce shrinkage ratio of molded part. Excessive mold temperature increases the temperature of part in the ejection process. Thus, the shrinkage ratio of part during subsequent cooling process after ejection is increased, and the shrinkage ratio of molded part is increased.

Melt temperature is the fifth important factor affecting shrinkage ratio of molded part, which contributes 5.981% to the total. With the increased melt temperature, the shrinkage ratio of GCP assisted CIM part shows a tendency of firstly almost unchanged and then decreasing. The higher temperature of the melt reaches, the higher temperature of the melt at the location of pouring gate is. The shrinkage ratio of molded part, at the same time, is getting smaller when the melt injected into mold cavity become more and more during the packing process.

Packing pressure affects little on shrinkage ratio of molding part, which contributes 1.569% to the total. Packing pressure can meet the compensation of the melt in the packing process when it reaches a value. At the same time, the change of pressure has little effects on shrinkage ratio of molded part.

4. Conclusions
This paper studied the influence of GCP assisted CIM process parameters on shrinkage ratio of a molded sample. The optimum process parameters combination to minimize shrinkage ratio of the molded part was obtained by using orthogonal experimental design and S/N ratio analysis method. Contribution rates of each parameter to the shrinkage ratio were obtained by using ANOVA. Finally, the effect mechanism of different process parameters on shrinkage ratio was also explained.

(1) For the standard stretch spline, the most important parameter affecting shrinkage ratio is GCP pressure, followed by packing time, injection pressure, mold temperature, melt temperature and packing pressure. Contribution rate of above six process parameters to shrinkage ratio are 61.232%, 13.985%, 7.260%, 5.921%, 5.918% and 1.569%, respectively.

(2) For the standard stretch spline, the optimum combination of process parameters is: mold temperature 50℃, melt temperature 220℃, injection pressure 70MPa, packing pressure 40MPa, packing time 15s, and GCP pressure 8MPa. Finally, the obtained shrinkage ratio of molded part is only 1.27%.

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