Reducing the Sink Marks of a Crystalline Polymer using External Gas-Assisted Injection Molding

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Received 26 June 2019; Accepted 30 July 2019; Published 29 February 2020

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External gas-assisted injection molding (EGAIM) has been used to reduce the sink marks of amorphous polymer products, but that of crystalline polymer products has not yet been reported. EGAIM of a crystalline polymer product was investigated in this study, and the influences of process parameters on the sink marks were discussed based on experiments. An isotactic polypropylene (iPP) product was fabricated by EGAIM under different process conditions. A uniform design was applied as an experimental design to investigate the influences of the process parameters on the sink marks. A regression equation was established to describe the quantitative relationship between the important parameters and sink marks in which a data-processing method was applied to determine the optimal value of \( \alpha \) at significant level \( \alpha \) to reduce the possibility of omission of some important parameters. The results show that EGAIM was effective in reducing the sink marks in these iPP products, and the most important parameters were the cooling time, gas pressure, and gas time. This study also provides the quantitative relationship between the important parameters and sink marks as reference for the research of EGAIM on crystalline polymer.

1. Introduction

External gas-assisted injection molding (EGAIM) is an unconventional molding process that efficiently fabricates products with high precision and high surface quality, especially in significantly reducing sink marks [1–3]. A sink mark is usually defined as “an unwanted depression or dimple on the surface of a molding due to localized shrinkage.” [4, 5]. The distinct localized shrinkage commonly results from a local thick-wall structure, such as ribs, bosses, and other similar structures [3, 6], which is also greatly affected by the process parameters in injection molding [7–9], including the melt temperature [10–12], packing pressure [13, 14], packing time [15], cooling time [16], injection pressure [17], and injection speed [18].

EGAIM is more complicated than the conventional injection molding (CIM) because of the introduction of gas. Gas with certain pressure is injected between the cavity surface of the mold and the solidified polymer formed during filling, after the cavity was filled by polymer. The gas pressure is maintained until the cooling process is terminated. The pressure on the solidified polymer pushes it to move and deform, which compensates the polymer shrinkage caused by temperature decrease during packing and cooling and reduce the sink marks.

The advantages and complexity of EGAIM have attracted the attention of researchers. Chen et al. [19] investigated the packing effects of EGAIM on the shrinkage and sink marks of plastic parts (ABS) under various rib designs and compared them with those of CIM. The results showed that EGAIM could further reduce the part shrinkage when the gas pressure and gas-packing time were both increased. Su et al. [20] also reduced the ghost marks in plastic parts of PA using EGAIM. Moreover, the quality of the parts was improved by increasing the mold temperature, melt temperature, injection speed, and pressure, although some limitations were experienced. Jiang et al. [21] discussed the relationship between the process parameters and part quality of ABS using the single-factor test method and developed a physical model that described the influence of gas-melting interaction on the sink marks [22].

The aforementioned studies focused on amorphous polymer products and did not explore the application of EGAIM to crystalline polymer products. Crystalline polymers are an important component in industrial production [23], aerospace [24], and pharmaceutical production [25]. In addition, the shrinkage of crystalline polymers is usually more obvious than that of amorphous polymers [26], and the sink marks of crystalline polymer products are usually larger than those of amorphous polymer products. Therefore, investigating
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the application of EGAIM to crystalline polymer products is important. In the present study, an iPP product was manufactured using EGAIM, and the influences of the process parameters on the sink marks of the iPP products were discussed. A regression equation was established to investigate the quantitative influence based on the experimental results in which a data-processing method was applied to determine the optimal value of $F_a$ at significant level $\alpha$ to reduce the possibility of omission of some important parameters. To verify the reduction of the sink marks of these iPP products by EGAIM, experiments with or without gas were carried out under an optimal condition, as calculated by the regression equation.

2. Experiments

A semi-crystalline iPP (T30S, Zhenhai Branch of Sinopec Corp., China) product was used in this study, and its parameters were as follows: melt flow index of 2.5 g/10 min, melting point of 167°C, density of 0.91 g/cm$^3$, and isotactic index of more than 94%. An injection molding machine (MA3800/2250, Haitian International Holdings Ltd., China) was used to manufacture the products with dimensions of 150 mm $\times$ 100 mm $\times$ 3 mm. After filling at a later time (delay time), an inert gas ($N_2$) with certain pressure was injected between the solidified polymer and cavity surface of the moving mold using a nitrogen pressure controller (C8-01, Beijing Chn-Top Machinery Group Co., Ltd., China). The sink marks of the crystalline polymer products were measured by a dial indicator (A0-12.7, Shanghai Siwei Instrument Manufacturing Co., Ltd., China), which has a measurement range of 12.7 mm and accuracy of 0.001 mm. The locations of gate, gas injections and measuring point are shown in Figure 1.

3. Data-Processing Method

Regression analysis is a set of statistical processes that estimates the relationship between the parameters and results. More specifically, regression analysis helps us understand how the
is commonly used in statistics [29]. However, the value of \( r \) results. The important parameters were selected by comparing the values of correlation coefficients, as expressed in Equation (2) [31].

\[
[r_{ij}] = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1P} & r_{1(P+1)} \\
r_{21} & r_{22} & \cdots & r_{2P} & r_{2(P+1)} \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
r_{n1} & r_{n2} & \cdots & r_{nP} & r_{nP+1}
\end{bmatrix}
\]

(2)

Generally, \( F \) should be calculated for every parameter in the regression analysis and is compared with pre-determined \( F_\alpha \) at significant level \( \alpha \), to determine whether the parameter is retained or not. In this study, the important parameters were obtained by comparing the correlation coefficients that should be included in the regression analysis. If the commonly used significance level, i.e., \( \alpha = 0.05 \) in the statistics is applied to the regression analysis in EGAIM, some important parameters might be omitted. Thus, this study introduced a method for modifying significant level \( \alpha \) and corresponding \( F_\alpha \).

In this work, the data processing can be summarized by the following steps.

**Step 1.** A set of significant level \( \alpha \) in a certain range and corresponding \( F_\alpha \) are obtained using the critical value table of the \( F \) distribution.

**Step 2.** The \( F_\alpha \) values of the important parameters are calculated using Equation (3) [32], where subscript \( X_i \) represents the selected important parameters using the comparison of the correlation coefficients.

\[
F_{X_i} = \frac{(r_{(p+1)})^2 - (r_{(i)})^2}{r_{ii} - (r_{ij})^2} ; i = 1, 2, \ldots, P + 1
\]

(3)

**Step 3.** Minimum \( F_{X_i} \) is compared with \( F_{\alpha} \) using Equation (4). If minimum \( F_{X_i} \) is less than \( F_{\alpha} \), \( F_{\alpha} \) cannot ensure that the important parameters are included in the regression equation. If minimum \( F_{X_i} \) is larger than or equal to \( F_{\alpha} \), \( F_{\alpha} \) is suitable for the regression analysis.

### Table 1: Uniform table remarking \( U_{30}(3^2 \times 5^1 \times 10^2) \) in EGAIM.

| Number | \( X_1 \) (°C) | \( X_2 \) (MPa) | \( X_3 \) (mm/s) | \( X_4 \) (MPa) | \( X_5 \) (s) | \( X_6 \) (s) | \( X_7 \) (MPa) | \( X_8 \) (s) |
|--------|----------------|----------------|----------------|----------------|------------|------------|------------|------------|
| 1      | 180            | 65             | 25             | 10             | 1          | 10         | 0          | 5          |
| 2      | 200            | 70             | 30             | 20             | 2          | 15         | 1          | 10         |
| 3      | 220            | 75             | 35             | 30             | 3          | 20         | 2          | 15         |
| 4      | —              | 80             | 40             | 40             | 4          | 25         | 3          | 20         |
| 5      | —              | 85             | 45             | 50             | 5          | 30         | 4          | 25         |
| 6      | —              | 90             | 50             | 60             | —          | 35         | 5          | 30         |
| 7      | —              | 95             | 55             | 70             | —          | 40         | 6          | —          |
| 8      | —              | 100            | 60             | 80             | —          | 45         | 7          | —          |
| 9      | —              | 110            | 65             | 90             | —          | 50         | 8          | —          |
| 10     | —              | 110            | 70             | 100            | —          | 55         | 9          | —          |

### Table 2: Uniform table.

| Number \( N_j \) | Parameter \( X_1 \) | Result \( Y \) |
|------------------|---------------------|----------------|
| \( N_1 \)        | \( X_{11} \)        | \( Y = X_{1(P+1)} \) |
| \( N_2 \)        | \( X_{11} \)        | \( Y = X_{1(P+1)} \) |
| \( \ldots \)     | \( \ldots \)        | \( \ldots \)    |
| \( N_n \)        | \( X_{n1} \)        | \( Y = X_{n(P+1)} \) |

The typical values of parameters change when any one of the results is varied [28]. One of the most important steps in regression analysis is the determination of optimal value \( F_{\alpha} \) at a significant level \( \alpha \), which directly determines whether parameters are introduced into the regression equation. In general, significant level \( \alpha = 0.05 \) is commonly used in statistics [29]. However, some important parameters are sometimes omitted in injection molding. Thus, a data-processing method was applied in this study to establish the optimal value of \( F_{\alpha} \) at a significant level \( \alpha \), which would reduce the possibility of omission of some important parameters. The data in the uniform table need to be dealt with by this processing method.

A uniform table was designed using a uniform design to reduce the number of experiments. The uniform table consists of \( N_j (j=1, 2, \ldots, n) \) experiments, \( X_i (i=1, 2, \ldots, P) \) parameters, and \( Y \) (recorded as \( X_j \), where \( j = P + 1 \)) results. The value of parameter \( X_i \) in the \( j \)th experiment is \( X_{ip} \) and result \( Y \) is recorded as \( X_{ip+1 \ldots 1} \), as listed in Table 2.

Correlation coefficient \( r_{ij} \) accurately describes the reliability between the parameters and results. The value of \( r_{ij} \) is positively correlated with the reliability between the parameters and results, as expressed in Equation (1) [30].

\[
r_{ij} = \frac{l_{ij} - \sum_{k=1}^{n} \left( X_{ik} - \bar{X}_i \right) \left( X_{jk} - \bar{X}_j \right)}{\sqrt{l_{ij} \sum_{k=1}^{n} \left( X_{ik} - \bar{X}_i \right)^2 \cdot \sum_{k=1}^{n} \left( X_{jk} - \bar{X}_j \right)^2}}
\]

\( i = 1, 2, \ldots, P + 1, \) \( j = 1, 2, \ldots, n \)

(1)
The matrix of the correlation coefficients is shown in the form of a heat map by combining Equations (1) and (2) to intuitively express the relationship between the parameters and sink marks, as shown in Figure 2. In the heat map, red and blue represent the positive and negative effects, respectively, and the number and shade of the colors indicate the correlation between the abscissa and ordinate. The value of the correlation coefficient between the gas time and sink marks is the largest value, which reaches −0.71. Thus, gas time is the most important parameter in EGAIM, and the negative sign indicates that the relationship between the gas time and sink marks is positive. The longer the gas time is, the smaller is the sink-mark value. The correlation coefficients of the cooling time and gas pressure are also large, which reach 0.32 and −0.23, respectively. Therefore, the gas time, cooling time, and gas pressure are important in the sink marks of the crystalline polymer products. The value of the correlation coefficient between the delay time and gas pressure is also large, which reaches 0.27. Thus, the influence of the delay time and gas pressure should not be neglected. The determination of the important parameters establishes a basis for exploring the

The aforementioned data-processing method provides the basis for selecting at significant level by comparing it with of the important parameters, which reduces the possibility of omission of some important parameters in the regression equation and improves the accuracy of this equation.

4. Results and Discussion

4.1. Correlation Coefficients of the Parameters. The sink marks of the crystalline polymer products measured by the dial indicator are listed in Table 3.

Table 3: Values of the sink marks of the crystalline polymer products.

| Number | \( X_1 \) (°C) | \( X_2 \) (MPa) | \( X_3 \) (mm/s) | \( X_4 \) (MPa) | \( X_5 \) (s) | \( X_6 \) (s) | \( X_7 \) (MPa) | \( X_8 \) (s) | \( X_9 \) (s) | \( Y = X_{10} \) (mm) |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1      | 180            | 105            | 40             | 10             | 5              | 35             | 3              | 5              | 1.5            | 0.264          |
| 2      | 220            | 110            | 35             | 80             | 2              | 25             | 8              | 10             | 2              | 0.155          |
| 3      | 220            | 70             | 60             | 90             | 3              | 10             | 1              | 30             | 1.5            | 0.0723         |
| 4      | 180            | 75             | 25             | 50             | 2              | 25             | 2              | 20             | 2              | 0.121          |
| 5      | 200            | 100            | 50             | 100            | 1              | 40             | 6              | 30             | 0.5            | 0.098          |
| 6      | 200            | 110            | 60             | 50             | 5              | 50             | 7              | 25             | 2              | 0.067          |
| 7      | 180            | 85             | 65             | 90             | 2              | 45             | 9              | 5              | 1              | 0.202          |
| 8      | 200            | 95             | 30             | 40             | 2              | 40             | 0              | 15             | 2.5            | 0.168          |
| 9      | 220            | 85             | 35             | 70             | 4              | 45             | 3              | 30             | 2.5            | 0.143          |
| 10     | 180            | 90             | 35             | 60             | 5              | 20             | 8              | 30             | 1              | 0.127          |
| 11     | 200            | 110            | 25             | 40             | 3              | 10             | 40             | 25             | 0              | 0.040          |
| 12     | 180            | 90             | 70             | 40             | 1              | 15             | 4              | 10             | 0.5            | 0.176          |
| 13     | 220            | 85             | 40             | 30             | 1              | 30             | 90             | 25             | 0              | 0.073          |
| 14     | 220            | 95             | 25             | 100            | 4              | 50             | 5              | 15             | 1              | 0.157          |
| 15     | 220            | 65             | 55             | 50             | 5              | 35             | 70             | 10             | 0              | 0.154          |
| 16     | 180            | 70             | 30             | 20             | 4              | 40             | 6              | 15             | 0.5            | 0.107          |
| 17     | 180            | 65             | 45             | 80             | 1              | 35             | 5              | 25             | 2              | 0.080          |
| 18     | 180            | 95             | 70             | 30             | 4              | 30             | 0              | 25             | 1.5            | 0.213          |
| 19     | 200            | 80             | 60             | 20             | 2              | 45             | 40             | 30             | 0              | 0.066          |
| 20     | 200            | 80             | 45             | 80             | 5              | 15             | 0              | 15             | 0.5            | 0.120          |
| 21     | 220            | 75             | 70             | 60             | 3              | 55             | 6              | 20             | 1.5            | 0.132          |
| 22     | 200            | 70             | 40             | 30             | 3              | 55             | 8              | 5              | 1.5            | 0.208          |
| 23     | 180            | 100            | 55             | 70             | 3              | 10             | 7              | 15             | 2.5            | 0.112          |
| 24     | 220            | 105            | 65             | 10             | 2              | 20             | 5              | 20             | 1              | 0.079          |
| 25     | 180            | 105            | 45             | 90             | 3              | 55             | 10             | 20             | 0              | 0.117          |
| 26     | 200            | 75             | 50             | 10             | 4              | 15             | 9              | 20             | 2.5            | 0.044          |
| 27     | 220            | 90             | 50             | 20             | 1              | 50             | 1              | 10             | 2              | 0.240          |
| 28     | 220            | 100            | 55             | 60             | 4              | 25             | 2              | 5              | 0.5            | 0.167          |
| 29     | 200            | 65             | 30             | 70             | 1              | 20             | 2              | 5              | 1              | 0.172          |
| 30     | 200            | 80             | 65             | 100            | 5              | 30             | 4              | 10             | 2.5            | 0.145          |

\[
\begin{align*}
\text{min} F_X < F_a; \text{ unsuitable} \\
\text{min} F_X \geq F_a; \text{ suitable}
\end{align*}
\]

Step 4. Correspondingly, this condition results in many suitable \( F_a \) values based on Step (2), but not all \( F_a \) values are optimal \( F_a \). To improve the accuracy, maximum \( F_a \) is considered as the optimal value from a large number of suitable \( F_a \) values.

The aforementioned data-processing method provides the basis for selecting \( F_a \) at significant level by comparing it with \( F_X \) of the important parameters, which reduces the possibility of omission of some important parameters in the regression equation and improves the accuracy of this equation.

4. Results and Discussion

4.1. Correlation Coefficients of the Parameters. The sink marks of the crystalline polymer products measured by the dial indicator are listed in Table 3.
quantitative relationship between the parameters and sink marks of the crystalline products in EGAIM.

4.2. Establishment of the Regression Equation. According to the calculation by Equation (3), the $F_X$ values of the cooling time, gas pressure, and gas time, were 3.19, 1.56, and 28.46, respectively. $F_X$ of the interaction of the gas pressure and delay time was 2.03. One of the most important steps in considering the regression equation is to determine $F_α$ at significant level $α$ to select the parameters. In general, $F_α$ at significant level $α$ should be defined before exploring the regression equation. However, $F_α$ depends on the preferences of different people $α$ is generally defined in statistics as 0.05, and $F_α = 2.9$ at significant level $α = 0.05$. If $F_α = 2.9$ is used to investigate the EGAIM parameters, the cooling and gas times are considered in the regression equation because $F_X > F_α = 2.9$. However, the gas pressure is omitted from the equation, which is unacceptable according to the aforementioned discussion. Significant level $α$ was thus adjusted to $α = 0.3$ to ensure that all important parameters were included into the regression equation. $F_α = 1.4$ at $α = 0.3$. All the $F_X$ values of the important parameters were larger than $F_α$, which avoided omitting the important parameters.

To obtain the quantitative relationship between the parameters and sink marks, the square term of the parameters and the interaction among the parameters were considered in the regression equation. The regression equation was investigated using the comparison between $F_X$ and $F_α = 1.4$, as expressed in Equation (5),

$$ Y = 0.0879 + 0.003025 \times X_6 + 0.02563 \times X_7 - 0.01050 \times X_8 + 0.1185 \times X_9 + 0.000223 \times X_5^2 - 0.03374 \times X_9^2 - 0.000514 \times X_7 \times X_8 - 0.00621 \times X_7 \times X_9 $$

(5)

The ratio of variation to the total variation for Equation (5) was described by the important coefficient $R^2$, which is a measure of the degree of fit. When $R^2$ more approaches unity, the response model fits the actual data better. The value of $R^2$ in Equation (5) is 85.37%, which is acceptable.

The regression equation of the sink marks in EGAIM was obtained according to the analysis of the correlation coefficients, which revealed the quantitative relationship between the important parameters and sink marks of the crystalline polymer products in EGAIM.

4.3. Discussion on the Regression Equation. The regression equation explores the influence of important parameters...
and the other unimportant parameters were combined according to the uniform design in a certain range, the sink marks of the crystalline polymer under different unimportant parameters are as those listed in Table 4.

The experimental results are shown in Figure 3, and the values of the sink marks under different unimportant parameters fluctuate from the average value and reach 0.097 mm. The difference between the average and predicted values of the regression equation is 0.006 mm and reaches 6.18%, which indicates that the accuracy of the regression equation and the influence of these parameters on the sink marks of crystalline polymer products are almost negligible. The regression equation establishes the quantitative relationship between the important parameters and sink marks of the crystalline polymer products in EGAIM.

4.4. Reduction of Sink Marks Using EGAIM. The aforementioned research obtained the optimal important parameters for the sink marks, including a cooling time of 55 s, gas pressure of 9 Mpa, gas time of 30 s, and delay time of 1 s. The other unimportant parameters were randomly determined from no. 14 in Table 4, and the material temperature, injection pressure, injection speed, packing pressure and packing time are 220°C, 70 Mpa, 60 mm/s, 60 Mpa, and 5 s, respectively.

Figure 4 compares the sink marks of the crystalline polymer products with or without gas. Figure 4(a) shows that the sink mark of the crystalline polymer products without the gas is 0.365 mm, whereas that with the gas is only 0.085 mm, as shown in Figure 4(b). The difference in the sink marks of the crystalline polymer products with or without gas is 0.280 mm. Thus, EGAIM significantly reduces the sink marks of the crystalline polymer products. Therefore, EGAIM obviously reduces the sink marks of these iPP products. The results provide sufficient evidence for the application of crystalline polymers in EGAIM.

### Table 4: Uniform table remarking $U_{15}(3^4 \times 5^4)$, including the unimportant parameters designed using the uniform design.

| Number | Material temperature ($^\circ$C) $X_1$ | Injection pressure (MPa) $X_2$ | Injection speed (mm/s) $X_3$ | Packing pressure (MPa) $X_4$ | Packing time (s) $X_5$ | Sink marks (mm) $Y$ |
|--------|--------------------------------------|---------------------------------|-------------------------------|-----------------------------|------------------------|-------------------|
| 1      | 180                                  | 110                             | 40                            | 80                          | 5                      | 0.116             |
| 2      | 220                                  | 110                             | 50                            | 20                          | 4                      | 0.111             |
| 3      | 200                                  | 110                             | 60                            | 60                          | 1                      | 0.096             |
| 4      | 180                                  | 80                              | 60                            | 20                          | 4                      | 0.096             |
| 5      | 200                                  | 100                             | 40                            | 20                          | 2                      | 0.092             |
| 6      | 180                                  | 100                             | 70                            | 40                          | 3                      | 0.103             |
| 7      | 220                                  | 100                             | 30                            | 100                         | 3                      | 0.102             |
| 8      | 200                                  | 80                              | 70                            | 100                         | 4                      | 0.096             |
| 9      | 200                                  | 70                              | 50                            | 80                          | 3                      | 0.089             |
| 10     | 200                                  | 90                              | 30                            | 40                          | 5                      | 0.096             |
| 11     | 180                                  | 90                              | 50                            | 100                         | 1                      | 0.085             |
| 12     | 220                                  | 90                              | 70                            | 80                          | 2                      | 0.087             |
| 13     | 220                                  | 80                              | 40                            | 40                          | 1                      | 0.091             |
| 14     | 220                                  | 70                              | 60                            | 60                          | 5                      | 0.085             |
| 15     | 180                                  | 70                              | 30                            | 60                          | 2                      | 0.103             |
5. Conclusion

In this study, the application of EGAIM to an iPP product was investigated by experiment. According to the results of this study, the following conclusions can be drawn. (1) EGAIM can significantly reduce the sink marks of these iPP products. (2) The cooling time, gas pressure, and gas time are important parameters that affect the sink marks of the crystalline polymer products according to the correlation coefficients. (3) The regression equation can correctly predict the sink marks of the crystalline polymer products when the important parameters in EGAIM are constant. In general, this study verifies the effectiveness of EGAIM on reducing the sink marks of crystalline polymer products and provides the quantitative relationship between the important parameters and sink marks of crystalline polymer products in EGAIM.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation under Grant Nos. 51575491, 51875525, and U1610112 and by the Natural Science Foundation of Zhejiang Province under Grant Nos. LY19E050004 and LY18E050020.

References

[1] S.-C. Nian, M.-H. Li, and M.-S. Huang, "Warpage control of headlight lampshades fabricated using external gas-assisted injection molding," *International Journal of Heat and Mass Transfer*, vol. 86, pp. 358–368, 2015.
[2] H.-Y. Su, S.-C. Nian, and M.-S. Huang, "Reducing ghost marks in injection-molded plastic parts by using external gas-assisted holding pressure," *International Communications in Heat and Mass Transfer*, vol. 66, pp. 1–10, 2015.
[3] S.-J. Liu, C.-H. Lin, and Y.-C. Wu, "Minimizing the sinkmarks in injection-molded thermoplastics," *Advances in Polymer Technology*, vol. 20, no. 3, pp. 202–215, 2001.
[4] D. Mathivanan and N. S. Parthasarathy, "Prediction of sink depths using nonlinear modeling of injection molding variables," *International Journal of Advanced Manufacturing Technology*, vol. 43, no. 7-8, pp. 654–663, 2009.
[5] J. Yu, H. Yong, L. Zhao, K. Agnieszka, Y. Wantai, and N. Jun, "Effect of monomer structure on real-time UV-curing shrinkage studied by a laser scanning approach," *Advances in Polymer Technology*, vol. 32, no. 1, pp. 4186–4193, 2013.
[6] C. Shen, L. Wang, W. Cao, and Q. Li, "Investigation of the effect of molding variables on sink marks of plastic injection molded parts using Taguchi DOE technique," *Polymer-Plastics Technology and Engineering*, vol. 46, no. 3, pp. 219–225, 2007.
[7] Y. Wang, L. Y. Chen, and X. M. Yang, "Numerical optimization of shrinkage and warpage on the injection molding process parameters of electrical connector," *Applied Mechanics and Materials*, vol. 868, pp. 183–191, 2017.
[8] M. C. R. Garcia, A. C. S. Netto, and A. J. Pontes, "Experimental study of shrinkage and ejection forces of reinforced polypropylene based on nanoclays and short glass fibers," *Polymer Engineering and Science*, vol. 58, no. 1, pp. 55–62, 2017.
[9] X. Wang, J. Gu, and C. Shen, "Warpage optimization with dynamic injection molding technology and sequential optimization method," *The International Journal of Advanced Manufacturing Technology*, vol. 78, no. 1, pp. 177–187, 2015.
[10] B. Y. Tay, L. Liu, N. H. Loh, S. B. Tor, Y. Murakoshi, and R. Maeda, "Injection molding of 3D microstructures by µPIM," *Micromsystem Technologies*, vol. 11, no. 2–3, pp. 210–213, 2005.
[11] R.-D. Chien, "Micromolding of biochip devices designed with microchannels," *Sensors and Actuators A: Physical*, vol. 128, no. 2, pp. 238–247, 2006.
[12] N.-S. Ong, H. L. Lee, and M. A. Parvez, "Influence of processing conditions and part design on the gas-assisted injection molding process," *Advances in Polymer Technology*, vol. 20, no. 4, pp. 270–280, 2001.
[13] C. D. Greene and D. F. Heaney, "The PVT effect on the final sintered dimensions of powder injection molded components," *Materials & Design*, vol. 28, no. 1, pp. 95–100, 2007.
[14] V. Speranza, U. Vietri, and R. Pantani, "Adopting the experimental pressure evolution to monitor online the shrinkage in injection molding," *Industrial & Engineering Chemistry Research*, vol. 51, no. 49, pp. 16034–16041, 2012.
[15] F. D. Santis, R. Pantani, V. Speranza, and G. Titomanlio, "Analysis of shrinkage development of a semicrystalline polymer during
injection molding,” Industrial & Engineering Chemistry Research, vol. 49, no. 5, pp. 2469–2476, 2010.
[16] R. Elleithy, I. Ali, M. Al-haj Ali, and S. M. Al-Zahrani, “Different factors affecting the mechanical and thermo-mechanical properties of HDPE reinforced with micro-CaCO₃,” Journal of Reinforced Plastics & Composites, vol. 30, no. 9, pp. 769–780, 2011.
[17] Y.-J. Xu, W. Yang, B.-H. Xie, Z.-Y. Liu, and M.-B. Yang, "Effect of injection parameters and addition of nanoscale materials on the shrinkage of polypropylene copolymer,” Journal of Macromolecular Science Part B, vol. 48, no. 3, pp. 573–586, 2009.
[18] J. Pomerleau and B. Sanschagrin, "Injection molding shrinkage of PP: experimental progress,” Polymer Engineering & Science, vol. 46, no. 9, pp. 1275–1283, 2010.
[19] S.-C. Chen, Y.-C. Lin, and S.-W. Huang, "Study on the packing effects of external gas-assisted injection molding on part shrinkage in comparison with conventional injection molding,” Polymer Engineering & Science, vol. 50, no. 11, pp. 2085–2092, 2010.
[20] H.-Y. Su, S.-C. Nian, and M.-S. Huang, "Reducing ghost marks in injection-molded plastic parts by using external gas-assisted holding pressure,” International Communications in Heat & Mass Transfer, vol. 66, pp. 1–10, 2015.
[21] S. Jiang, W. Zheng, J. Zhang, and J. Li, "Experimental study on the Influence of parameters on the plastic parts quality of external gas-assisted injection molding," Applied Mathematics & Information Sciences, vol. 6, no. 3, pp. 665–671, 2012.
[22] S. Jiang, J. Tao, and J. Li, "Study on the mechanism of the packing process and sink mark in external gas-assisted injection molding," Advances in Mechanical Engineering, vol. 6, 853142 pages, 2014.
[23] M. Altan, "Reducing shrinkage in injection moldings via the Taguchi, ANOVA and neural network methods," Materials & Design, vol. 31, no. 1, pp. 599–604, 2010.
[24] D. Garcia-Gonzalez, S. Garzon-Hernandez, and A. Ariasb, "A new constitutive model for polymeric matrices: application to biomedical materials," Composites Part B: Engineering, vol. 139, pp. 117–129, 2018.
[25] R. P. Brannigan and A. P. Dove, "Synthesis, properties and biomedical applications of hydrolytically degradable materials based on aliphatic polyesters and polycarbonates," Biomaterials Science, vol. 5, no. 1, pp. 9–21, 2017.
[26] D. L. Poerschke, A. Braithwaite, D. Park, and F. Lauten, "Crystallization behavior of polymer-derived Si-O-C for ceramic matrix composite processing," Acta Materialia, vol. 147, pp. 329–341, 2018.
[27] A. R. Higgs, M. J. Maughon, R. T. Ruland, and M. C. Reade, "Effect of uniform design on the speed of combat tourniquet application: a simulation study," Military Medicine, vol. 181, no. 8, pp. 753–755, 2016.
[28] K.-H. Kim, J. C. Park, Y. S. Suh, and B.-H. Koo, "Interactive robust optimal design of plastic injection products with minimum weldlines," The International Journal of Advanced Manufacturing Technology, vol. 88, no. 5–8, pp. 1333–1344, 2017.
[29] J. F. Mudge, T. J. Barrett, K. R. Munkittrick, and J. E. Houlahan, "Negative consequences of using α = 0.05 for environmental monitoring decisions: a case study from a decade of Canada's environmental effects monitoring program," Environmental Science & Technology, vol. 46, no. 17, pp. 9249–9255, 2012.
[30] W.-Y. Zhang, Z. W. Wei, B.-H. Wang, and X.-P. Han, "Measuring mixing patterns in complex networks by spearman rank correlation coefficient," Physica A: Statistical Mechanics and its Applications, vol. 451, no. 1, pp. 440–450, 2016.
[31] M. Z. Belmecheri, M. Ahfir, and I. Kale, "Automatic heart sounds segmentation based on the correlation coefficients matrix for similar cardiac cycles identification," Biomedical Signal Processing & Control, vol. 43, pp. 300–310, 2018.
[32] L. P. Ma, Regression Analysis: Regression Analysis [M], Machinery Industry Press, p. 150, 2014.