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The simulation of the warpage rule of the thin-walled part of polypropylene composite based on the coupling effect of mold deformation and injection molding process

DOI 10.1515/secm-2015-0195

Received May 1, 2015; accepted October 1, 2016; previously published online November 8, 2016

Abstract: Aiming at the problem that a thin-walled plastic part easily produces warpage, an orthogonal experimental method was used for multiparameter coupling analysis, with mold structure parameters and injection molding process parameters considered synthetically. The plastic part deformation under different experiment schemes was comparatively studied, and the key factors affecting the plastic part warpage were analyzed. Then the injection molding process was optimized. The results showed that the important order of the influence factors for the plastic part warpage was packing pressure, packing time, cooling plan, mold temperature, and melt temperature. Among them, packing pressure was the most significant factor. The optimal injection molding process schemes reducing the plastic part warpage were melt temperature (260°C), mold temperature (60°C), packing pressure (150 MPa), packing time (2 s), and cooling plan 3. In this situation, the forming plate flatness was better.

Keywords: coupling analysis; process optimization; thin-walled plastic part; warpage.

1 Introduction

With the development of computer, home appliance, communication, and automotive industry, people are more and more inclining to pursuit thin-walled, complex plastic part. Injection molding can complete plastic part with complex shape and precise size at a time. The molding process is a result of complex, nonlinear interaction

effects of multiparameter coupling, which easily results in various defects, such as short shot, warpage, burn, weld line, and sink mark. Among them, warpage has the most obvious influence on plastic part quality [1–3]. Therefore, the injection simulation computer aided engineering (CAE) technology is often used to quantitatively analyze the injection molding process in the mold design process, to research the effects of mold structure and process parameters on plastic part quality, and to predict the occurrence of the design and manufacturing defects of the plastic part, which will provide theoretical basis for obtaining high-quality products.

Xu [4] regarded part warpage as the optimization goal and used the orthogonal experimental method combined with the mold flow analysis software Moldflow to optimize the injection molding process parameters for the thin-walled plastic part. Dong et al. [5] quantitatively analyzed shrinkage and warpage using a simulation program and studied the significant influence of the injection molding process parameters on it. Liao and Liu [6] simulated the packing process of plastic part using the Moldflow software and studied the effect of packing pressure and packing way on the plastic part warpage. Dong et al. [7] simulated a phone shell using numerical simulation technology and obtained a set of optimal process parameters, which make warpage minimum. Tang et al. [8] analyzed the effects of various injection molding process parameters on plastic part warpage and sought the optimal process parameters for plastic part warpage using the Taguchi method. Mlekusch [9] proposed a method to control plastic part warpage and calculated residual stress in the injection molding process using a nonlinear viscoelastic model. Ozcelik and Sonat [10] studied the thin-walled plastic part warpage with different thicknesses, and the result showed that the packing pressure had the greatest effect on it. Erzurumlu and Ozcelik [11] studied simulative plastic part warpage with different materials and different structures using the Moldflow software and optimized the process parameters. Yena et al. [12] designed the orthogonal experiment using the Taguchi method, simulated it using the Moldflow software, optimized the gating system, and

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reduced the warpage. Huang and Tai [13] used the Taguchi experimental design method to optimize the injection molding process and simulated the molding process of plastic part using the C-MOLD software. Research results showed that mold temperature, packing time, melt temperature, and packing pressure were the major factors affecting the plastic part warpage, whereas gate size and filling time had little effect on it. Jansen et al. [14] selected seven kinds of thermoplastic plastics, namely, PS, ABS, PC, HIPS, PP, PBT-GF30, and HDPE, and studied their effects on material's shrinkage and warpage under the condition of a change in injection speed, mold temperature, and packing pressure. Experimental results showed that packing pressure and melt temperature were the greatest factors affecting shrinkage and warpage, whereas mold temperature and injection speed had little effect on it. Zhang et al. [15] researched the influence of process parameters on plastic part warpage using the orthogonal experimental method together with the Moldflow software. Azaman et al. [16] studied and compared the deflection and warpage of the thin-walled parts under different injection materials; the important parameters reducing volumetric shrinkage and warpage using lignocellulosic polymer composites for molded thin-walled parts [17]; the optimum parameter ranges making in-cavity residual stresses of the thin-walled parts minimum [18]; the effect of process parameters on shrinkage and warpage of the thin-walled parts and the optimization of the shrinkage and warpage of the thin-walled parts [19]; and the relationship between the types of thin-walled molded parts and in-cavity residual stresses and warpage [20].

The previously mentioned injection studies for thin-walled parts have not considered plastic part warpage caused by mold deformation. However, because of the great packing pressure and the influence of nonuniform temperature in thin-walled parts due to the injection molding process, mold deformation is much larger than that of normal injection molding. In recent years, some scholars begin to pay attention to mold deformation for thin-walled injection molding. Chang et al. [21] proposed that nonuniform flow pressure and mold temperature in the injection molding process can cause cavity deformation. Chen and Huang [22] used Moldflow analysis results as boundary conditions for the ANSYS analysis of cavity deformation and researched mold deformation. Liu et al. [23] studied the stiffness analysis of mold cavity using ANSYS and Moldflow software. They divided cavity surface into different areas, selected the average value of cavity surface stress obtained from Moldflow simulation as surface load input into ANSYS, and simulated the mold cavity, making the results closer to the actual injection molding process.

In this paper, Moldflow and ANSYS software combined with the orthogonal experimental method were used for multiparameter coupling analysis, with mold structure parameters and injection molding process parameters considered synthetically. Then the key factors and influence rules affecting plastic part warpage were found. The optimal process parameter combination and the optimal mold structure were obtained, and the goal of reducing plastic part warpage was achieved.

2 Finite element modeling and research schemes

2.1 Finite element modeling

2.1.1 Finite element modeling of Moldflow

Plastic part is an air filter sheet of mobile air conditioner. It has length, width, and average wall thickness of 238, 230, and 1 mm, respectively, as shown in Figure 1. The mould layout form is one module and one cavity, and the pinpoint gate is applied to the injection simulation. A finite element model is created using a double-sided unit type mesh, as shown in Figure 2.

The crystalline polymer selected is polypropylene, and the melt fluidity of the material is good. Its basic performance parameters are shown in Table 1.

2.1.2 Finite element modeling of ANSYS

First, the injection mold of the air filter sheet is created by the three-dimensional design software UG, as shown in Figure 3. Templates, top rods, and other institutions are simplified, then local holes and fillets are removed. The mold is meshed using the ANSYS software, and then a simplified

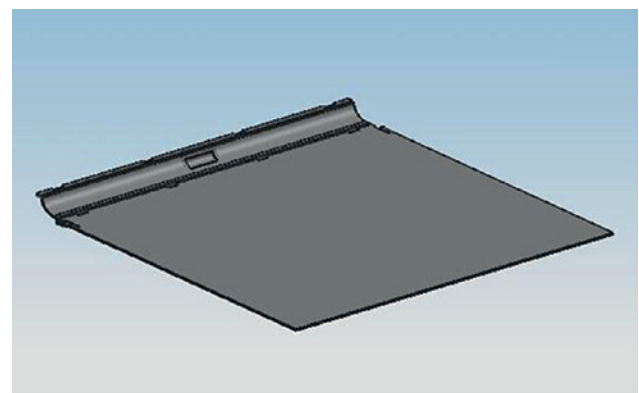


Figure 1: The thin-walled model.

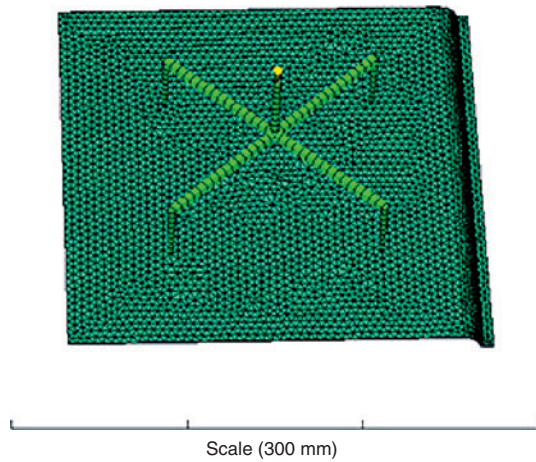


Figure 2: The finite element model of thin-walled part.

Table 1: The basic performance parameters of material polypropylene.

Material performance	Parameter value
Thermal conductivity (W/m °C)	0.15
Specific heat capacity (J/kg °C)	3100
Recommended injection temperature (°C)	230
Recommended top temperature (°C)	93
Recommended mold temperature (°C)	50

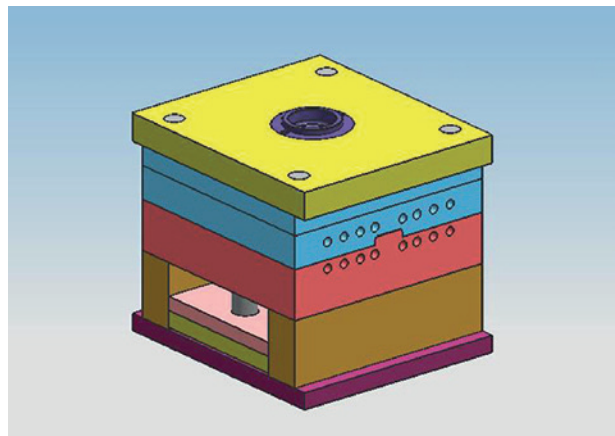


Figure 3: The mold structure.

finite element model is obtained, as shown in Figure 4. The part's materials and the basic properties of the mold's main force structure are shown in Tables 2 and 3, respectively.

2.2 Research schemes

With minimum warpage as the optimization goal and with melt temperature, mold temperature, packing pressure,

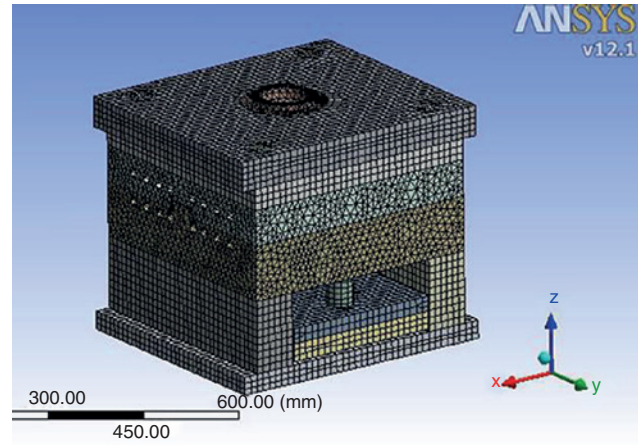


Figure 4: The finite element model of mould.

Table 2: Classification of the part's mold materials.

Material	Parts
P20 Steel	Fixed template, dynamic template, mold core, mold cavity
45 Steel	Fixed clamping plate, moving clamping plate, square iron, shore

Table 3: Basic properties of the part's mold materials.

Mold material	P20 Steel	45 Steel
Elasticity modulus (MPa)	2.12E5	2.04E5
Poisson's ratio	0.288	0.28
Thermal conductivity (W/mK)	35	49.8
Yield strength (MPa)	850	360
Ultimate strength (MPa)	1080	690
Specific heat capacity (J/kg °C)	460	468.2
Coefficient of linear expansion (K)	1.250E-5	1.232E-5

packing time, and mold structure (cooling plan) as variables, the research was conducted using the orthogonal experimental method.

According to the injection mold temperature field based on ANSYS analysis, four cooling plans are designed for the purpose of uniform temperature field, as shown in Table 4. The cooling pipes are symmetrically distributed and centered on the plastic part, as shown in Figure 5.

According to the characteristics of thin-walled injection molding, four levels for each factor are taken. An orthogonal experimental table with five factors and four levels is obtained, as shown in Table 5, and then the L_{16} orthogonal array is used, as shown in Table 6.

Table 4: Cooling plan parameters.

Cooling plan	Cooling circuit	Cooling pipe diameter/mm	Pipe distance from the center of the plastic part/mm
1	4	8	18
2	8	8	18
3	8	From the outer to the center 6 8 10 12	18
4	8	From the outer to the center 6 8 10 12	Respectively 12 18 24 30

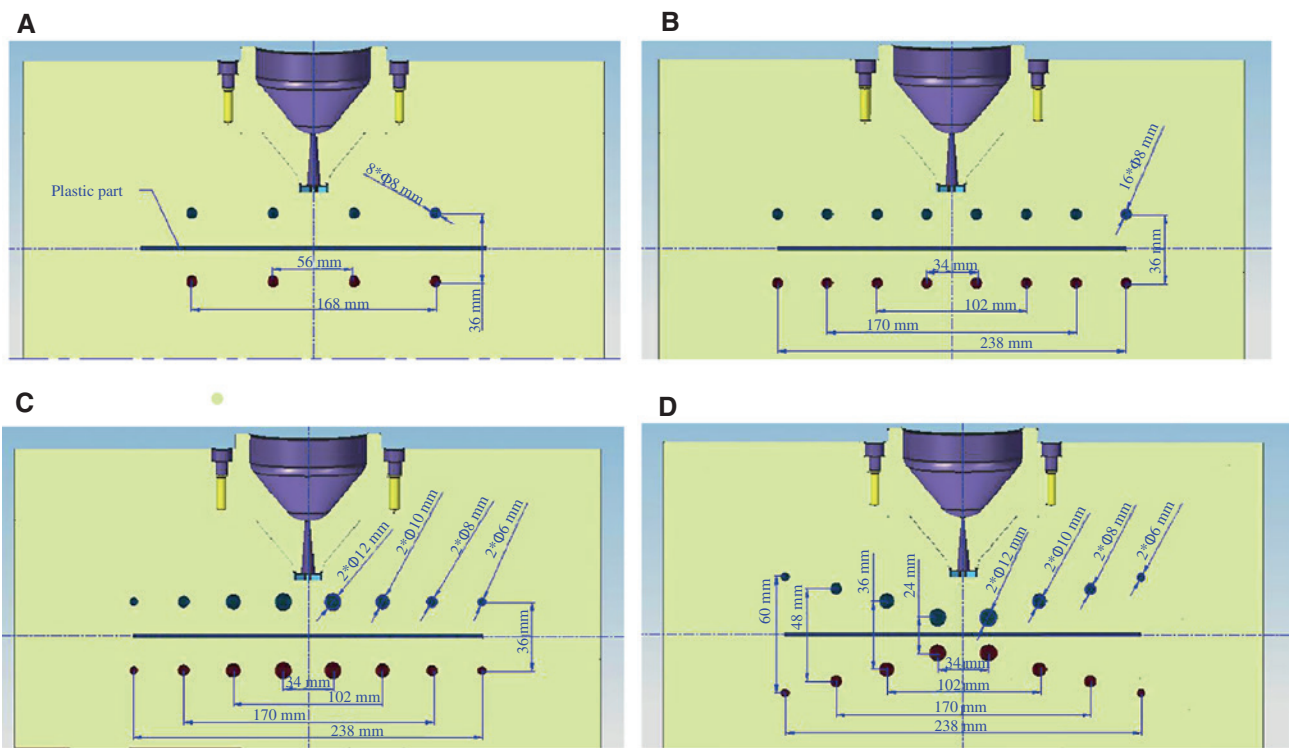


Figure 5: The cooling plans: (A) cooling plan 1, (B) cooling plan 2, (C) cooling plan 3, and (D) cooling plan 4.

Table 5: Orthogonal experimental table.

Level	Melt temperature (A) (°C)	Mold temperature (B) (°C)	Packing pressure (C) (MPa)	Packing time (D) (s)	Cooling plan (E)
1	230	20	30	2	1
2	245	40	70	6	2
3	260	60	110	10	3
4	275	80	150	14	4

3 Result analysis and discussion

3.1 Calculation of the plastic part deformation

The total deformation (deviation) ΔE of the plastic part in the Z direction includes deviation ΔE^m caused by injection

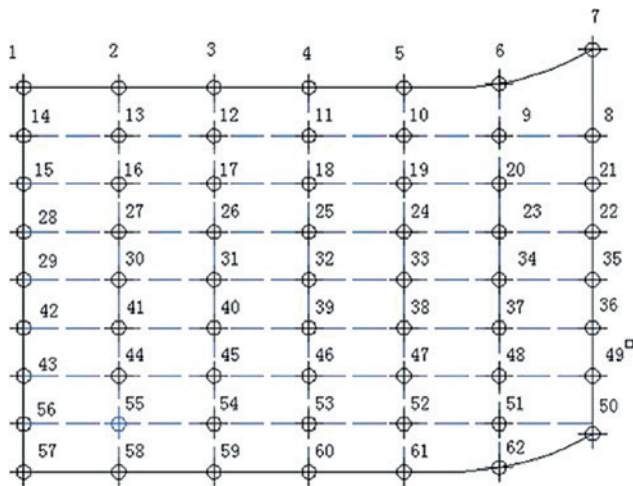
molding process and deviation ΔE^a caused by mold deformation, and the formula is as follows:

$$\Delta E = \Delta E^m + \Delta E^a. \tag{1}$$

Sixty-two data points are uniformly taken from the plastic part, as shown in Figure 6. The deviations ΔE^m and ΔE^a of each point of the plastic part in the Z direction after

Table 6: L_{16} orthogonal array.

Experiment no.	A	B	C	D	E
1	230	20	30	2	1
2	230	40	70	6	2
3	230	60	110	10	3
4	230	80	150	14	4
5	245	20	70	10	4
6	245	40	30	14	3
7	245	60	150	2	2
8	245	80	110	6	1
9	260	20	110	14	2
10	260	40	150	10	1
11	260	60	30	6	4
12	260	80	70	2	3
13	275	20	150	6	3
14	275	40	110	2	4
15	275	60	70	14	1
16	275	80	30	10	2

**Figure 6:** The distribution of data points.

injection are calculated, and then the total deformation ΔE is calculated.

3.2 Deformation analysis

Sixty-two data point deviations of every simulation experimental scheme are analyzed, and 16 groups of data normal distribution are obtained, as shown in Figure 7. It can be seen that the data obtained from 16 groups of schemes conform to normal distribution. The absolute deviation of data points reflects the local deformation degree of each point. Among them, some of the absolute deviations of scheme 2 data points are maximum, which reach 6.5 mm, indicating that the local deformation of the plastic part is

maximum. Schemes 6, 8, 11, and 16 also have larger local deformation, whereas the absolute deviations of the data points of schemes 4, 7, 10, 12, and 13 are small, indicating that these plastic parts do not have prominent local deformation parts. Among them, the absolute deviation of scheme 13 is minimum, only 0.79 mm.

The standard deviation [24] is the cumulation of the local warpage of 62 points of plastic part and reflects the overall deformation degree of the plastic part. It can be seen from Figure 8 that the standard deviation of scheme 2 is up to 2.314 mm, indicating that the overall deformation of the plastic part is maximum. The standard deviation of schemes 6, 11, and 16 are also larger, so the overall deformation is also larger, whereas schemes 4, 7, 10, 12, and 13 are smaller, so the overall deformation is smaller. These results are consistent with the local deformation trend of the plastic part. The plastic part of scheme 2 is not only maximum local deformation but also maximum overall deformation, so scheme 2 is the worst. Schemes 6, 11, and 16 are also both larger deformation, so the three schemes are also poor, whereas schemes 4, 7, 10, 12, and 13 are better.

It can be seen from Table 6 that the better schemes 4, 7, 10, and 13 all need great packing pressure (150 MPa) in addition to scheme 12.

3.3 Significance analysis of the influence factors

K_1 , K_2 , K_3 , and K_4 express the sum of simulation results of every experimental scheme, which have the same factor level, respectively, such as K_1 -A data, the sum of simulation results of four experiment schemes of factor A (melt temperature) level 1 (230°C), namely, the sum of the standard deviation of schemes 1–4. K_3 -C data are the sum of simulation results of four experiment schemes of factor C (packing pressure) level 3 (110 MPa), namely, the sum of the standard deviation of schemes 3, 8, 9, and 14, and other analogies. k_1 , k_2 , k_3 , and k_4 are the average value of K , namely, $K_1/4$, $K_2/4$, $K_3/4$, and $K_4/4$. Range R describes the difference of the maximum and the minimum average values of experiment results of each parameter under different levels, namely,

$$R = k_{\max} - k_{\min}. \quad (2)$$

Table 7 is the analysis results of range of the experiment data. Range R [25] reflects the effects of the corresponding factors on the index in the experiment. The levels of the factor that has a big range cause a big difference in the experiment results; thus, the factor is

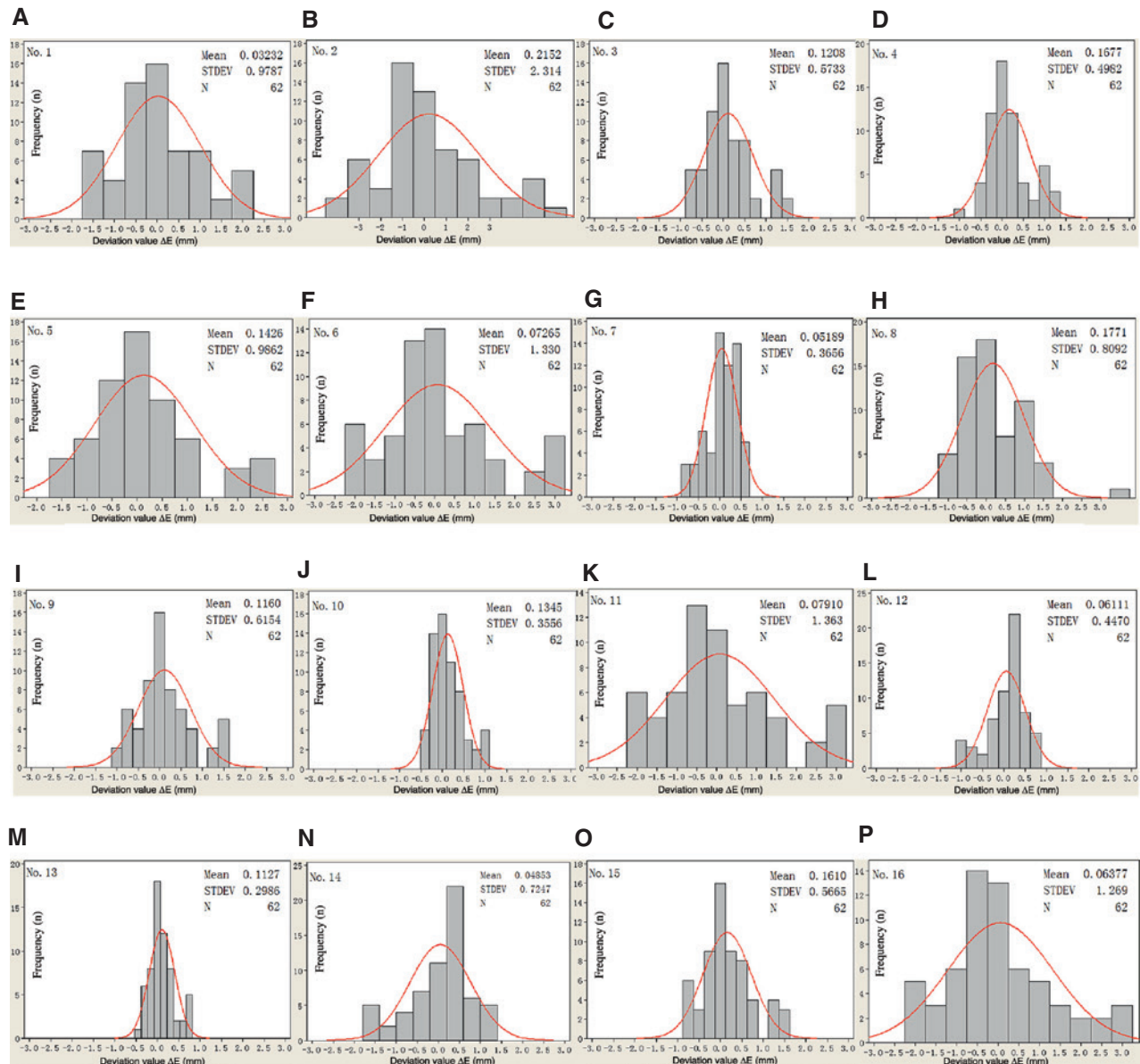


Figure 7: The normal distribution of 16 groups of experiment schemes data points: (A) scheme 1, (B) scheme 2, (C) scheme 3, (D) scheme 4, (E) scheme 5, (F) scheme 6, (G) scheme 7, (H) scheme 8, (I) scheme 9, (J) scheme 10, (K) scheme 11, (L) scheme 12, (M) scheme 13, (N) scheme 14, (O) scheme 15, (P), and scheme 16.

significant. However, the factor that has a small range is not significant. It can be analyzed from Table 7 that the important order of the significance of the influence factors is as follows: packing pressure, packing time, cooling plan, mold temperature, and melt temperature.

$$S_i = q \sum_{i=1}^q (k_i - \bar{y})^2 \quad (3)$$

Equation 3 is the sum of squared deviations. It quantitatively estimates the influence degree of each factor on the

plastic part warpage, where q expresses the level number and $\bar{y}$ is the average value of k_i .

$$f = q - 1 \quad (4)$$

In Equation 4, f expresses freedom degree of each factor.

Variance F expresses a significant level of the influence of each factor.

Table 8 is the analysis results of variance of the experiment data. It can be seen that packing pressure is the significant factor affecting warpage, and F value is 0.601,

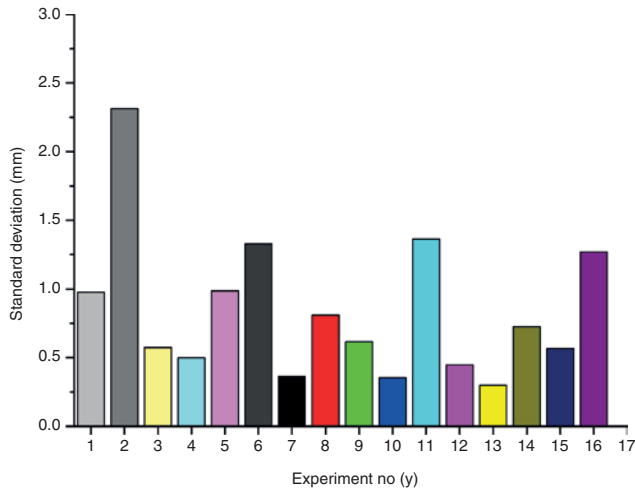


Figure 8: The standard deviation distribution of 16 schemes.

Table 7: Analysis results of range of the experiment data.

Factor	A	B	C	D	E
K_1	4.364	2.879	4.940	2.516	2.710
K_2	3.491	4.724	4.314	4.785	4.564
K_3	2.781	2.868	2.723	3.184	2.649
K_4	2.859	3.024	1.518	3.010	3.572
k_1	1.091	0.720	1.235	0.629	0.678
k_2	0.873	1.181	1.079	1.196	1.141
k_3	0.695	0.717	0.681	0.796	0.662
k_4	0.715	0.756	0.380	0.753	0.893
R	0.396	0.464	0.855	0.567	0.479

followed by packing time, mold temperature, cooling plan, and melt temperature.

3.4 Optimization of process parameters

Figure 9 shows the relationship of factor level and index K . For factor A, $K_1 > K_2 > K_4 > K_3$. Hence, level 3 of factor A is the best, level 3 of factor B is the best, level 4 of factor C

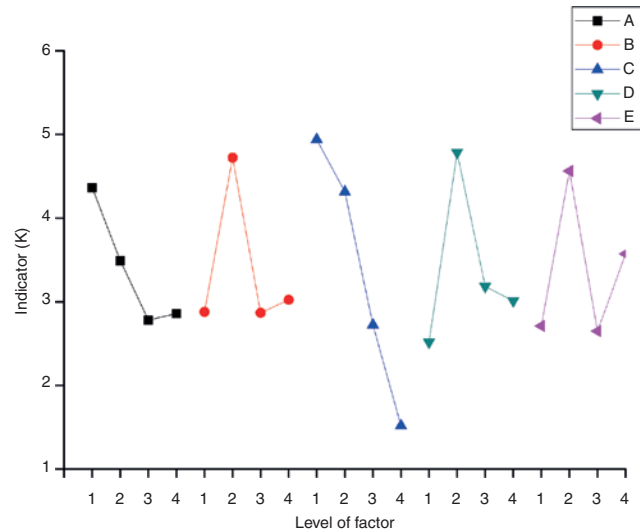


Figure 9: The relationship of factor level and index.

is the best, level 1 of factor D is the best, and level 3 of factor E is the best, namely, the optimal process scheme is $A_3B_3C_4D_1E_3$. That is, the plastic part warpage is minimum using the injection molding process of melt temperature 260°C , mold temperature 60°C , packing pressure 150 MPa, packing time 2 s, and cooling plan 3.

3.5 Analysis of the optimization effect

The plastic part is the result of mold flow analysis by the Moldflow software and mold deformation analysis by the ANSYS software using the optimal process scheme $A_3B_3C_4D_1E_3$. It can be known that the maximum deviation $\Delta E_{\max}^a$ caused by mold deformation is 0.105 mm (as shown in Figure 10) and the maximum deviation $\Delta E_{\max}^m$ caused by injection molding process is 0.65 mm (as shown in Figure 11). Figure 12 is the normal distribution of the simulated deviation data obtained from the optimal process scheme. It can be seen that the maximum deformation $\Delta E_{\max}^e$ of the plastic part in the Z direction is

Table 8: Analysis of variance table.

Factor	Sum of squared deviations S_i	Degree of freedom f	F	Significance
Melt temperature A ($^\circ\text{C}$)	0.403	3	0.134	
Mold temperature B ($^\circ\text{C}$)	0.611	3	0.204	
Packing pressure C (MPa)	1.800	3	0.600	Significant influence
Packing time D (s)	0.723	3	0.241	Significant influence
Cooling plan E	0.605	3	0.202	
Error	0.004			
Sum	4.146	15		

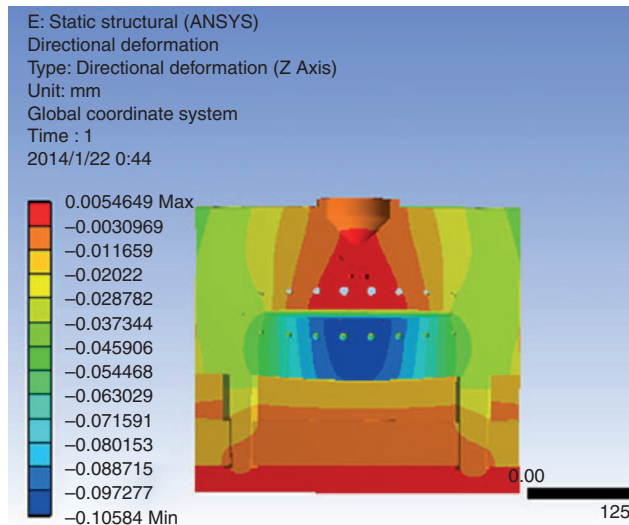


Figure 10: The plastic part deformation caused by mold cavity.

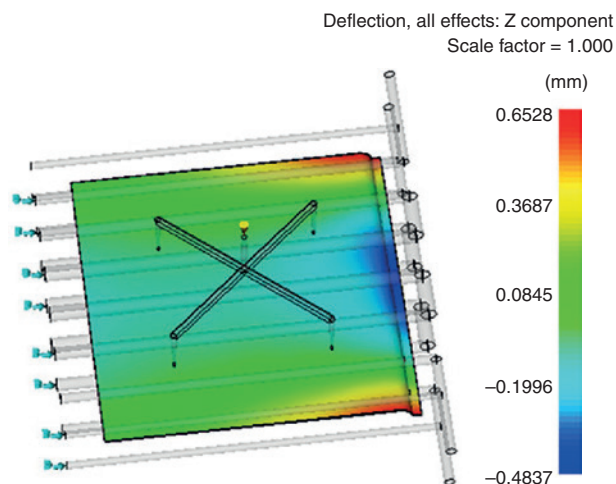


Figure 11: The plastic part warpage.

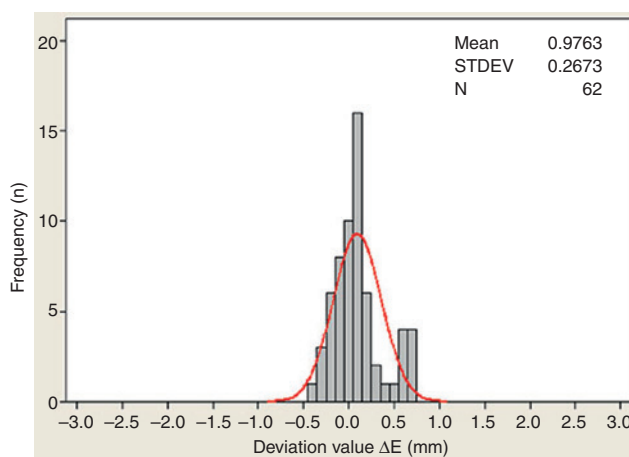


Figure 12: The data points normal distribution under the optimal experiment scheme.

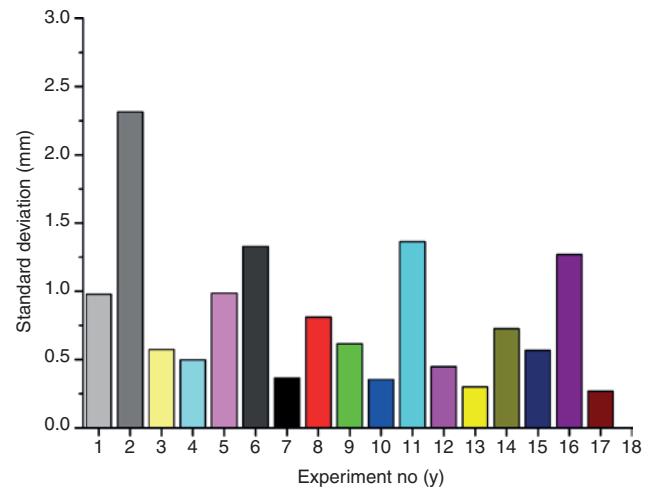


Figure 13: The comparison of standard deviation.

0.75 mm, which is better than schemes 1–16. It can be seen from Figure 13 that the standard deviation of the optimal scheme 17 is smaller than that of 16 schemes, indicating that the scheme is optimal. Figure 14 shows fitting graphs of the plastic part of experiment scheme 13 and the optimal scheme. It can be seen that the warpage degree of the plastic part reduces significantly after optimization and plate flatness is better.

These results show that a comprehensive optimization effect is significant through the mold deformation and process parameters coupling in this paper, and it can reduce the thin-walled plastic part warpage obviously and improve the quality of the plastic part.

4 Conclusions

- As to the local deformation of the plastic part, experiment scheme 2 is maximum; thus, it is the worst scheme. By contrast, the local deformation of schemes 4, 7, 10, 12, and 13 are small; thus, they are better. As to the overall deformation of the plastic part, scheme 2 is also the worst scheme, whereas schemes 4, 7, 10, 12, and 13 are better.
- It can be known from the analysis of range of the orthogonal experiment data that the important order of the influence factors for the plastic part warpage is as follows: packing pressure, packing time, cooling plan, mold temperature, and melt temperature. It can be known from the analysis of variance of the experiment data that packing pressure is the significant factor affecting warpage, followed by packing time, mold temperature, cooling plan, and melt temperature.

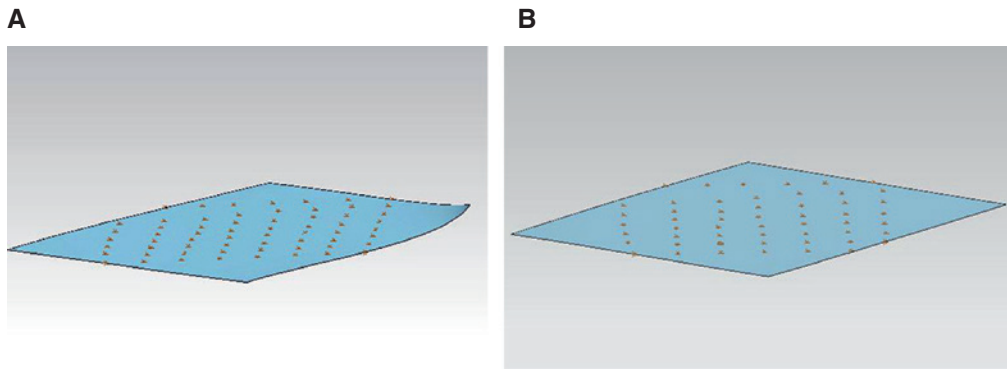


Figure 14: UG fitting graphs: (A) before optimization and (B) after optimization.

3. It can be known from the optimization of process parameters that the optimal process scheme is $A_3B_3C_4D_1E_3$ in the injection molding process, namely, the plastic part warpage is minimum using the injection molding process of melt temperature 260°C , mold temperature 60°C , packing pressure 150 MPa, packing time 2 s, and cooling plan 3.
4. The plastic part is the result of mold flow analysis by the Moldflow software and mold deformation analysis by the ANSYS software using the optimal process scheme. As a result, the warpage degree of the plastic part reduces significantly, and plate flatness is better. It indicates that a comprehensive optimization effect is significant through the mold deformation and process parameters coupling in this paper, and it can reduce the thin-walled plastic part warpage obviously and improve the quality of the plastic part.
5. This paper studied the effect of mold structure parameters and injection molding process parameters on the warpage of the thin-walled part. Previous works studied only the effect of injection molding process parameters on the warpage of the thin-walled part.

Acknowledgments: This work was supported by the Original Program of Chongqing Foundational and Frontier Research Plan (grant no. cstc2013jcyjA70015) and the Science and Technology Research Program of Education Council of Chongqing (grant no. KJ080407).

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