The effective factors in the warpage problem of an injection-molded part with a thin shell feature

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1.Introduction

- The development of communication and electronic consumer products, such as portable computers and mobile telephones, has had the trend for products to be light, thin, short, and small.
- As a result, the shapes of products are changing and more features have to be packed into smaller volumes within the housing. One way of doing this is to reduce the wall thickness of the housing parts to give more space for the tightly packed components inside
- However, as the wall thickness of plastic parts becomes thinner, the injection molding operation becomes more difficult.
- Hence, the industry has the demand for techniques of plastic injection molding to produce plastic parts with thin wall features.

2. The warpage problem in injection molding

- It is an important issue in plastic injection molding to predict the warpage problem before manufacturing takes place.
- There have been some publications on this topic, both on theoretical simulation and on experimental results.

1. The thermal warpage resulting from unbalanced cooling in a flat plate of amorphous polymer, which revealed that the warpage phenomenon of the molded product results from the bending moment due to the asymmetrical stress distribution over the thickness of the plastic parts.
2. The warpage is predicted from the temperature difference between the upper and lower surfaces, the temperature distribution, flow-induced shear stress, shrinkage, and anisotropic mechanical properties caused by fiber orientation.

3. The packing pressure is shown to have a significant effect on the shrinkage of the molded part, higher packing pressures resulting in lower shrinkage, both in the in-plane and through-thickness direction.
4. The result shows that a thinner gate gives a more equable shrinkage for approximately the same applied packing pressure. Clearly, with a constant packing pressure and a thick gate, there is no way to produce a part with uniform shrinkage.
5. A simple elastic model was used to study the effect of in-mold shrinkage on the final product dimensions and residual stress distribution. It was shown clearly that longer holding time produces less final length shrinkage.

3.Motive and aim

- In the procedure of injection molding, as the wall thickness decreases, it becomes harder to get the plastic material to flow successfully through the distance to the desired area.
- Owing to a greater portion of the melted plastic material being in contact with the relatively cold mold wall at thinner sections, heat dissipates quickly, and the material freezes quickly.
- Consequently, higher shear stress on the material and more molecular orientation will be expected, which may contribute to warpage.

- From a previous literature review, the effective factors of warpage in the injection-molded products can be identified, including the filling time, mold temperature, gate dimensions, melt temperature, packing pressure and packing time.
- The purpose of this research is to analyze the effective factors of warpage in injection-molded items applying the Taguchi method.
- Computer simulations of the injection molding process will be carried out to obtain the warpage data. Then, the contribution percentage of each factor can be found and the optimum set of parameters driving the effective factors in injection molding can be determined to produce a product with the minimum warpage.

4.Taguchi's experimental method

- The following descriptions outline the parameter design procedure：

1. To designate the quality characteristic
2. To determine the effective factors and levels
3. To select the appropriate orthogonal arrays
4. To select the appropriate formulations of quality characteristics, the SN (signal-to-noise) ratio is one of the measurement indexes for quality characteristics.
5. The SN ratio can be obtained from experimental data.
6. Auxiliary tables and response diagram: Taguchi proposed auxiliary tables and a response diagram.

Table 1
The orthogonal array L27(3^{13}) used in this research

Trial No.	Column												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	1	1	3	2	1	2	1	3	1	3	2

When the orthogonal array is set up, the interactive effect should be designated as an additional effective factor, if there is interaction between any two of the effective factors.

This can be carried out using the interactive orthogonal array presented in Table 2.

Table 2
L27(3^{13}) interaction column

Column	Column												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	(1)	3	2	2	6	5	5	9	8	8	12	11	11
		4	4	3	7	7	6	10	10	9	13	13	12
2		(2)	1	1	8	9	10	5	6	7	5	6	7
			4	3	11	12	13	11	12	13	8	9	10
3			(3)	1	9	10	8	7	5	6	6	7	5
				2	13	11	12	12	13	11	10	8	9
4				(4)	10	8	9	6	7	5	7	5	6
					12	13	11	13	11	12	9	10	8
5					(5)	1	1	2	3	4	2	4	3
						7	6	11	13	12	8	10	9
6						(6)	1	4	2	3	3	2	4
							5	13	12	11	140	9	8
7							(7)	3	4	2	9	3	2
								12	11	13	2	8	10
8								(8)	1	1	5	3	4
									10	9	4	7	6
9									(9)	1	7	2	3
										8	3	6	5
10										(10)	6	4	2
												5	7
11											(11)	1	1
												13	12
12												(12)	1
													11
13													(13)

5. Experimental method

- Simulation of the injection molding process using computer software has made promising progress recently.
- In this research, the commercial mold flow analysis software, C-MOLD™, is used to carry out all of the injection molding experiments.
- These simulations provide information such as the distribution and variation of the temperature, pressure, flow rate, skin property, molecular orientation, shear stress and shear rate of the material in the filling, packing and cooling stages.
- In addition, the molding conditions of the injection process can be optimized.

Table 3
The physical properties of PC/ABS

Specific heat, C_p (J/kg°C)	1871
Glass transition temperature, T_g (°C)	112
Thermal expansion coefficient, α (μm/m°C)	74
Elastic modulus, E (MPa)	2.63×10^3
Poisson's ratio, υ	0.23
Thermal conductivity, K (w/m°C)	0.27

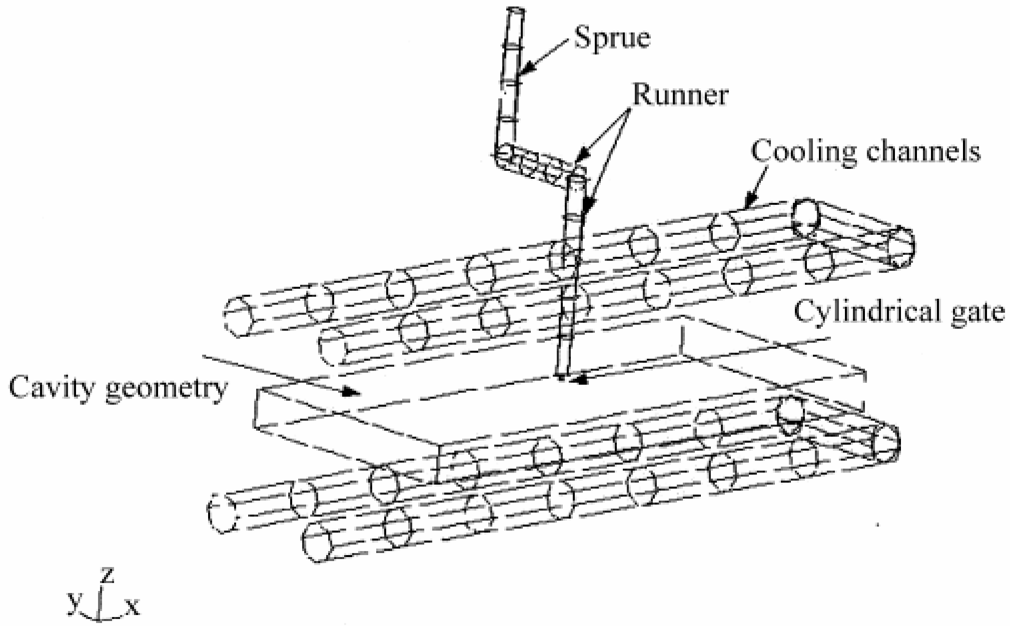

Fig. 1. The configuration of the cooling channels and the cavity geometry.

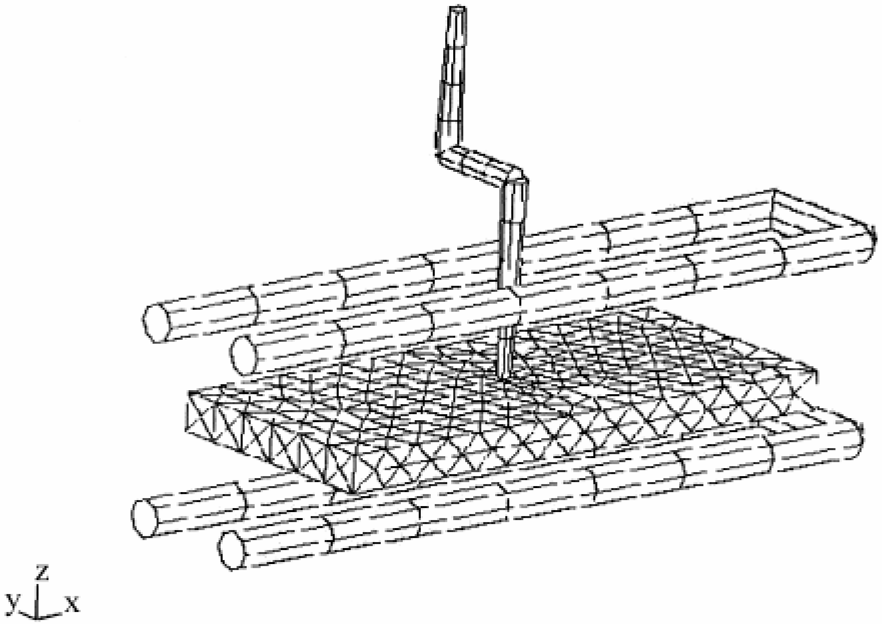

Fig. 2. The finite element meshes of the geometrical model.

Table 4
The three levels of effective factors for experimental variance

Factors	Levels		
	1	2	3
Mold temperature, x1 (°C)	55	70	85
Melt temperature, x2 (°C)	240	265	290
Filling time, x3 (s)	0.1	0.3	0.5
Gate dimension, x4 (mm)	0.8	1	1.2
Packing pressure, x5 (MPa)	60%	75%	90%
Packing time, x6 (s)	0.6	0.8	1

Table 5
The orthogonal array with three levels and the results of experiment

Trial No.	Control factor													Signal factor (120 MPa)		Average Z	SN
	x1	x2	x1×x2	x1×x2	x3	x4	x5	x2×x3	x6	*e*	x2×x3	*e*	*e*	0	+4		
1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.2273	0.2273	0.2273	12.87
2	1	1	1	1	2	2	2	2	2	2	2	2	2	0.1572	0.3519	0.2546	11.29
3	1	1	1	1	3	3	3	3	3	3	3	3	3	0.5392	0.6448	0.5920	4.52
4	1	2	2	2	1	1	1	2	2	2	3	3	3	0.1128	0.1128	0.1128	18.95
5	1	2	2	2	2	2	2	3	3	3	1	1	1	0.3120	0.3120	0.3120	10.12
6	1	2	2	2	3	3	3	1	1	1	2	2	2	0.1558	0.1558	0.1558	16.15
7	1	3	3	3	1	1	1	3	3	3	2	2	2	0.2320	0.2320	0.2320	12.69
8	1	3	3	3	2	2	2	1	1	1	3	3	3	0.1009	0.1009	0.1009	19.92
9	1	3	3	3	3	3	3	2	2	2	1	1	1	0.3203	0.3203	0.3203	9.89
10	2	1	2	3	1	2	3	1	2	3	1	2	3	0.4624	0.4624	0.4624	6.70
11	2	1	2	3	2	3	1	2	3	1	2	3	1	0.1176	0.1290	0.1233	18.17
12	2	1	2	3	3	1	2	3	1	2	3	1	2	0.2245	0.2763	0.2504	11.98
13	2	2	3	1	1	2	3	2	3	1	3	1	2	0.2746	0.2746	0.2746	11.23
14	2	2	3	1	2	3	1	3	1	2	1	2	3	0.1137	0.1137	0.1137	18.88
15	2	2	3	1	3	1	2	1	2	3	2	3	1	0.1027	0.1027	0.1027	19.77
16	2	3	1	2	1	2	3	3	1	2	2	3	1	0.1031	0.1031	0.1031	19.73
17	2	3	1	2	2	3	1	1	2	3	3	1	2	0.1045	0.1045	0.1045	19.62
18	2	3	1	2	3	1	2	2	3	1	1	2	3	0.2029	0.2029	0.2029	13.85
19	3	1	3	2	1	3	2	1	3	2	1	3	2	0.1823	0.1823	0.1823	14.78
20	3	1	3	2	2	1	3	2	1	3	2	1	3	0.1503	0.1249	0.1376	17.19
21	3	1	3	2	3	2	1	3	2	1	3	2	1	0.1104	0.1187	0.1146	18.81
22	3	2	1	3	1	3	2	2	1	3	3	2	1	0.0888	0.0888	0.0888	21.03
23	3	2	1	3	2	1	3	3	2	1	1	3	2	0.2096	0.2096	0.2096	13.57
24	3	2	1	3	3	2	1	1	3	2	2	1	3	0.1532	0.1532	0.1532	16.29
25	3	3	2	1	1	3	2	3	2	1	2	1	3	0.0966	0.0966	0.0966	20.30
26	3	3	2	1	2	1	3	1	3	2	3	2	1	0.1672	0.1672	0.1672	15.54
27	3	3	2	1	3	2	1	2	1	3	1	3	2	0.0905	0.0905	0.0905	20.87

Table 6
The response table of SN ratio

Level	Factor					
	x1	x2	x3	x4	x5	x6
1	12.933	12.923	15.364	15.157	17.461	17.624
2	15.548	16.221	16.033	14.966	15.893	15.433
3	17.598	16.934	14.681	15.927	12.724	13.021
$\lvert \Delta T \rvert$	4.65	4.011	1.352	0.961	4.737	4.603

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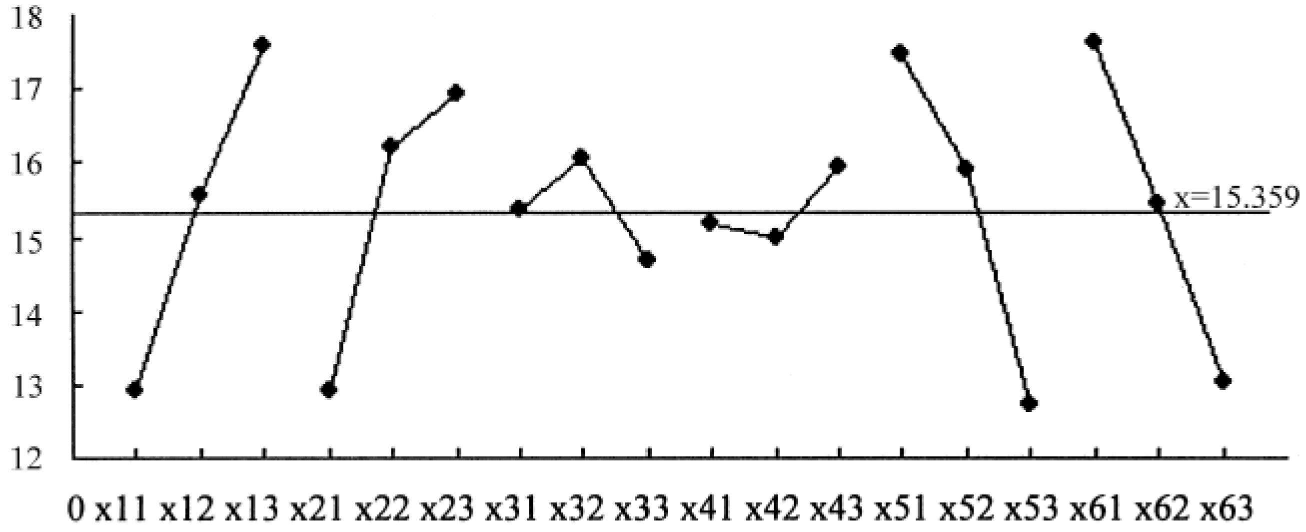

Fig. 3. The response diagram of SN.

Table 7
Analysis of variance

Source of variation	Sum of squares	Degrees of freedom	Mean of square	F_0	$F_{0.05}$	SS'	Percent sum of squares
x1	0.063	2	0.0315	6.18[a]	3.7389	0.0528	12.14
x2	0.057	2	0.0285	5.59[a]	3.7389	0.0468	10.76
x3	0.011	2	0.0055	1.08	3.7389		
x4	0.003	2	0.0015	0.29	3.7389		
x5	0.078	2	0.0390	7.65[a]	3.7389	0.0678	15.59
x6	0.052	2	0.0260	5.10[a]	3.7389	0.0418	9.61
x1×x2	0.113	4	0.0285	4.92[a]	3.1122	0.1028	23.63
x2×x3	0.022	4	0.0055	1.08	3.1122		
e	0.036	6	0.006				
Total	0.435	26				0.435	100.0
Pooled e	0.072	14	0.0051			0.123	28.27

[a] Significant items.

Table 8
The variation of warpage values with different packing pressures

Packing pressure (%)	40	50	60	70	80	85	90	100
Warpage (mm)	0.102	0.094	0.090	0.084	0.087	0.096	0.108	0.134

Table 9
The variation of warpage values with different mold temperatures

Mold temperature (°C)	40	45	50	65	85	95	105
Warpage (mm)	0.162	0.162	0.101	0.135	0.090	0.086	0.114

Table 10
The warpage values for different melt temperatures

Melt temperature (°C)	230	240	245	250	270	280	290	310	330	350
Warpage (mm)	0.104	0.108	0.121	0.163	0.164	0.129	0.090	0.092	0.114	0.094

Table 11
The irregular variation of warpage with different packing times

Packing time (s)	0.1	0.3	0.4	0.6	0.9	1	1.1	1.2	1.5	2
Warpage (mm)	0.101	0.170	0.125	0.090	0.088	0.087	0.133	0.129	0.138	0.138

Table 12
The variation of warpage with change in filling time

Filling time (s)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.9	1.2	1.5
Warpage (mm)	0.089	0.109	0.095	0.092	0.090	0.151	0.169	0.228	0.372	0.811

Table 13
The warpage values related to the gate dimension

Gate dimension (s)	0.2	0.4	0.45	0.5	0.6	1.2
Warpage (mm)	0.121	0.098	0.097	0.090	0.093	0.090

7. Conclusions

1. Of all the effective factors regarding warpage in the injection molding of a thin shell part, the packing pressure is the most influential factor, which shows a contribution rate of 15.59%. The second is the mold temperature at 12.14%, followed by the melt temperature at 10.76%, and the packing time at 9.61%. The less influential factors are the gate dimension and filling time. The interaction of factors between mold temperature and melt temperature has shown a contribution rate of 23.63%, which must not be neglected.

2. Using a Taguchi orthogonal array can effectively reduce the number of trials in experimental design. The effective factors can be determined using ANOVA.
3. Each factor's effect on the warpage has been characterized, which may be helpful in determining more precise process conditions in injection molding.
4. In future studies, other methods of optimization may be employed, such as regression analysis, to achieve an ideal set of process conditions for minimizing warpage in injection molding.