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Influence of processing parameters on warpage according to the Taguchi experiment †

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Abstract

An automotive triangle trim was chosen as a research model, and the influence of processing parameters was determined with the Taguchi experimental method. An L_{27} (3^{13}) orthogonal array was constructed to investigate the significance of each factor (mold temperature, melt temperature, injection time, V/P switchover, packing pressure, and packing time). The computer-aided engineering software Moldflow was employed to determine the extent of warpage. The influence of processing parameters was analyzed by obtaining the signal-to-noise ratio and by conducting a range analysis. Furthermore, the processing parameters for minimizing warpage were optimized. Subsequently, the optimization packing condition for warpage minimization based on the filling conditions.

Keywords: Injection molding; Warpage; Taguchi; Process optimization

1. Introduction

With the development of lightweight automobiles, plastic has been used extensively in the automobile manufacturing industry. Almost 80% of plastic automotive parts are processed through injection molding. In the process, various molding defects are observed in plastic products, such as warpage, volume contraction, weld lines, and air traps. Potential reasons include the wide variety of plastic raw materials, complicated mold cavity structures, different control strategies for molding apparatuses, and diverse rheological and mechanical properties. The warpage of plastic parts is an important indicator of quality in plastic products and affects not only product assembly and performance but also the quality of product appearance. The most simple and effective method of preventing warpage is to optimize the molding process parameters.

Using a sequential simplex method [1], Behrooz Farshi studied the thin-walled parts of a vehicle and determined the effect of molding process parameters on warpage and volume shrinkage. Wu-lin Chen simulated the injection molding process in Moldflow, designed an experiment according to a response surface methodology, and identified the process parameters that minimize volume shrinkage and warpage [2]. Kurtaran analyzed the effects of injection molding parameters (mold temperature, melt temperature, packing pressure, packing time, and cooling time) on the warpage of an automobile lampshade with a neural network model and a Genetic algorithm (GA). This researcher detected the minimum optimal warping process parameters [3]. Kitayama noted that the variable pressure profile effectively reduces warpage via the surrogate-based optimization technique, throughout which a radial basis function network is used [4]. Chuang MT and Yang YK applied gray relational analysis to obtain an optimal combination of parameters for the injection molding process [5]. Many methods have been employed extensively to optimize the design of the parameters for such a process, including the Taguchi method [6]. Babur Ozcelik analyzed the molding process of mobile phone shells with Finite element (FE) simulation software and detected the factor that exerts maximum influence on warpage through orthogonal experimental design. This researcher also optimized the parts through CATIA structural analysis [7]. Wei Guo proposed an effective methodology that integrated the design of experiments and GA to minimize sink mark depth and to optimize permanent optimization design [8, 9]. Dong-Gyu Ahn conducted numerical analyses and experiments to determine the influence of injection molding parameters on the core shift and optimize the injection molding conditions of a plastic battery case with thin and deep walls [10]. Jung Hyun Cho described the Polymethylmethacrylate (PMMA) deformation caused by injection molding at high temperatures and relocated the injection gate

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Table 1. Properties of the material.

PVT properties		Mechanical	
Melt density (g/cm^3)	0.88147	Solid	1.0579
Recommended mold temperature (°C)	30	Elastic modulus (MPa)	1340
Recommended melt temperature (°C)	220	Shear modulus (MPa)	481
Ejector	101	Poisson ratio	0.392
Filler	20% Talc		

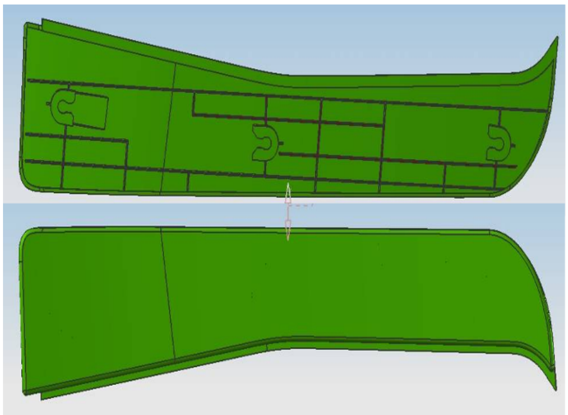


Fig. 1. Front and back view of the 3D model.

to minimize this deformation [11]. Phuong NguyenThi investigated the flow behavior of different coating conditions in an in-mold coating process.

The current study simulates the injection molding process of a workpiece on a machine. The interior triangle of an automobile is taken as an example, and the FE software Moldflow is used. This process reflects the melt filling, packing, and cooling procedures to accurately prediction warping deformation. The effect of processing parameters is determined with the Taguchi experimental method, and the processing parameters include mold temperature, melt temperature, injection time, V/P conversion points, packing pressure, and packing time.

2. Experimental design

2.1 Mode and material

To meet the requirements of FE analysis, the 3D solid model proposed in this study is illustrated in CATIA, as shown in Fig. 1. The model includes a workpiece that measures 435 mm × 90 mm × 30 mm and has a wall thickness of 2.5 mm. The material (ID 12517) was chosen from the Moldflow software, and the manufacturer is Kingfa Sci & Tech Co. Ltd. The material properties of the parts are presented in Table 1. Given the size characteristics of the solid model components, pre-treatment modeling and meshing processes are performed with Moldflow. Fig. 2 shows that the FE model of the parts consists of 31595 grid units, and the grid is of "Double layer grid" type. A gating system and a cooling system are established in Moldflow software with reference to the mold design.

Table 2. Processing parameters and levels.

Factor	A (°C)	B (°C)	C (s)	D	E	F (s)
	T_{mold}	T_{melt}	t_{inject}	V/P	P_{press}	P_{time}
Level 1	20	210	1.4	97%	60%	12
Level 2	40	230	1.5	98%	80%	13
Level 3	60	250	1.6	99%	100%	14

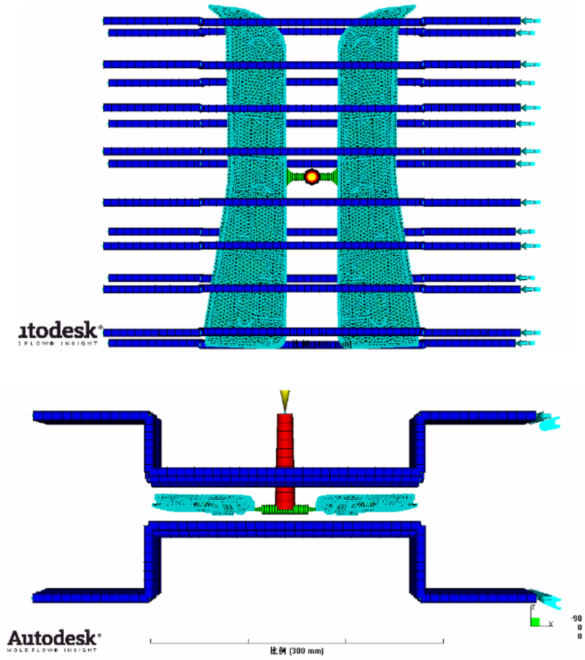


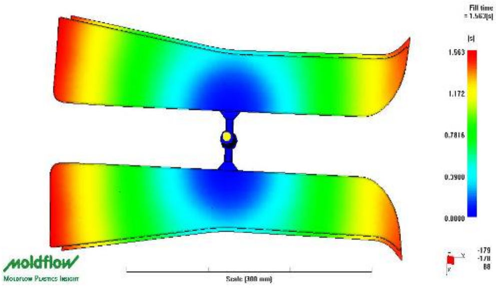
Fig. 2. FE model of the mold and the parts.

2.2 Taguchi experimental design

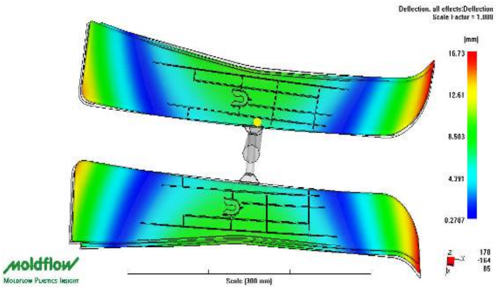
The Taguchi method is an experimental method designed by Japanese quality expert Dr. Taguchi. This method helps significantly reduce the number of iterations in the experiment and lower experimental cost. To investigate the influence of formation parameters on warpage, this study selected mold temperature, melt temperature, injection time, V/P switch point, packing pressure, and packing time as the research factors. Volume control managed the V/P switch point, and the packing pressure was 60%~100% of the injection pressure. The chosen research factors are presented in Table 2. The L_{27} orthogonal table was utilized based on the Taguchi method, and the parameters of the experimental design are listed in Table 3.

3. Results and discussion

The FE software Moldflow was used to design the parame-



(a) Fill time



(b) Warpage

Fig. 3. Results of computer-aided engineering.

ters of the 27 experiments in this study and in conducting the simulation analysis for the injection molding formation process. Fig. 3 displays the key results of this analysis. By conducting this simulation, a designer can intuitively query the occurrence of melt flow conditions in cavities and molding defects. Fig. 3(a) exhibits the results for filling time. The flow of the melt in the cavity can be observed in the figure at any time, and the melt filling times of the ends of the two parts are almost equal. Thus, the casting system design is relatively reasonable and does not cause unbalanced flow. Table 3 records the warping deformation during the 27 experiments.

3.1 Mean analysis

The average result for each factor in each level is determined during the experiments, along with a series of K values (average value). Table 4 and Fig. 4 show the K values of the factors at different levels. The average value chart indicates that the extent of product warpage decreases slowly with injection time, whereas the V/P conversion point and packing time increase. Melt temperature increases, and the extent of warpage decreases rapidly at first. Subsequently, the degree of influence drops significantly. Packing pressure increases, and the extent of warpage drops rapidly. This result illustrates that among all the studied factors, packing pressure exerts the strongest effect on warpage. Table 4 shows the results of average analysis and suggests that a significant difference implies a considerable influence on warpage. Therefore, the factors affecting warpage degree include packing pressure, melt temperature, packing time, V/P conversion point, injection time, and mold temperature (from high to low).

Table 3. Design and results of the Taguchi experiment.

NO	T_{mold} A (°C)	T_{melt} B (°C)	t_{inject} C (s)	V/P D	P_{press} E	P_{time} F (s)	*Warpage* (mm)
1	20	210	1.4	97%	60%	12	3.325
2	20	210	1.4	97%	80%	13	3.167
3	20	210	1.4	97%	100%	14	3.037
4	20	230	1.5	98%	60%	12	3.275
5	20	230	1.5	98%	80%	13	3.073
6	20	230	1.5	98%	100%	14	2.972
7	20	250	1.6	99%	60%	12	3.243
8	20	250	1.6	99%	80%	13	3.049
9	20	250	1.6	99%	100%	14	2.929
10	40	210	1.5	99%	60%	13	3.279
11	40	210	1.5	99%	80%	14	3.120
12	40	210	1.5	99%	100%	12	3.001
13	40	230	1.6	97%	60%	13	3.247
14	40	230	1.6	97%	80%	14	3.084
15	40	230	1.6	97%	100%	12	3.014
16	40	250	1.4	98%	60%	13	3.247
17	40	250	1.4	98%	80%	14	3.070
18	40	250	1.4	98%	100%	12	3.054
19	60	210	1.6	98%	60%	14	3.303
20	60	210	1.6	98%	80%	12	3.128
21	60	210	1.6	98%	100%	13	3.006
22	60	230	1.4	99%	60%	14	3.230
23	60	230	1.4	99%	80%	12	3.109
24	60	230	1.4	99%	100%	13	2.996
25	60	250	1.5	97%	60%	14	3.180
26	60	250	1.5	97%	80%	12	3.142
27	60	250	1.5	97%	100%	13	2.996

Table 4. Results of Signal-to-noise ratio (SNR) analysis.

Level	Mold temperature A	Melt temperature B	Injection time C	V/P conversion D	Packing pressure E	Packing time F
1	−9.872	−9.965	−9.926	−9.913	−10.260	−9.943
2	−9.890	−9.853	−9.865	−9.892	−9.840	−93871
3	−9.882	−9.826	−9.853	−9.839	−93543	−9.829
Delta	0.017	0.139	0.073	0.074	0.717	0.114
Rank	6	2	5	4	1	3

3.2 SNR analysis

SNR denotes the signal-to-noise ratio. The Taguchi method is used to determine the experiment that is least influenced by noise. A maximum SNR represents the minimum sensitivity of the new noise energy, thereby optimizing the experiment conditions. A small amount of warpage is preferred. Therefore, the minimum SNR eigenvalue can be applied to describe war-

Table 5. Results of range analysis.

Level	Mold temperature A	Melt temperature B	Injection time C	V/P conversion D	Packing pressure E	Packing time F
1	3.118	3.152	3.137	3.132	3.259	3.143
2	3.124	3.111	3.115	3.125	3.105	3.118
3	3.121	3.100	3.110	3.105	2.999	3.102
Delta	0.006	0.052	0.027	0.027	0.259	0.042
Rank	6	2	5	4	1	3

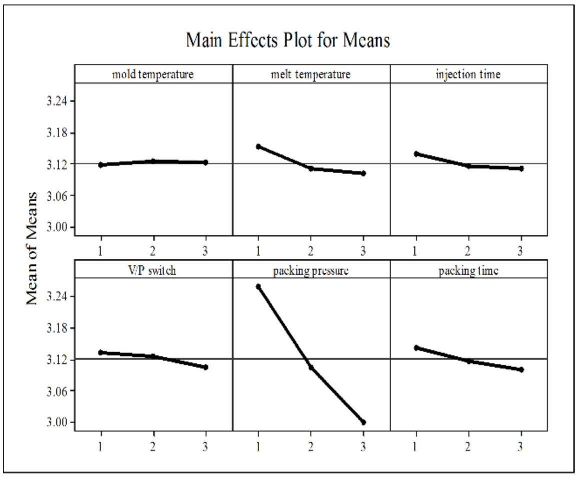


Fig. 4. Results of range analysis.

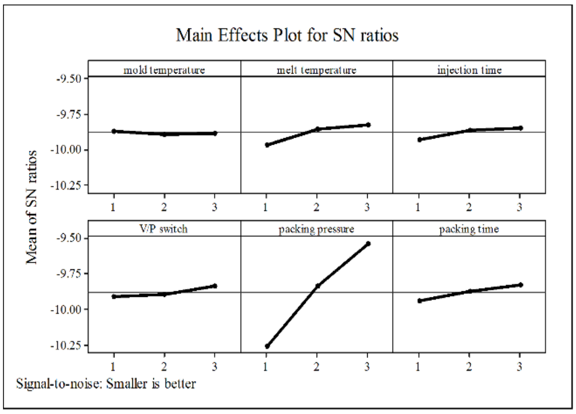


Fig. 5. SNR of the factors.

page characteristics. The formula for SNR calculation is expressed as follows:

$$\frac{S}{N} = -10\log[[\frac{1}{n}]\sum_{i=1}^{n}(w_i^2)], \quad (1)$$

where w_i is the amount of warpage in each experiment. Fig. 5 depicts the average SNR of each factor. A large ratio implies the weak effect of noise on performance. With regard to the

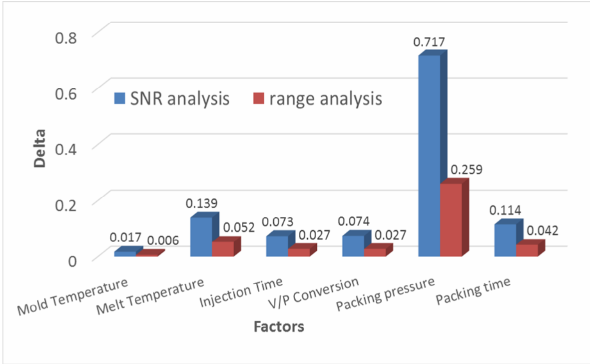


Fig. 6. Results of SNR analysis and range analysis.

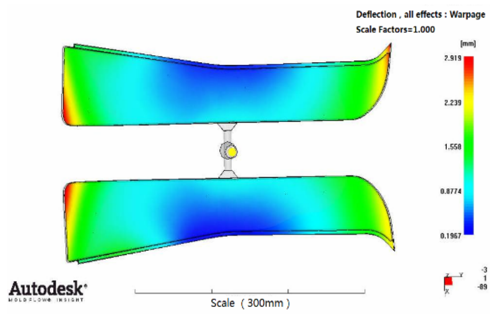


Fig. 7. Warpage result with the optimal processing parameters.

minimization problem, the degree of warpage under the corresponding level is small. The process parameters that generate minimal warpage are denoted by A1B3C3D3E3F3. The ideal result is obtained with high-level melting temperature, injection time, V/P conversion points, packing pressure, and packing time in combination with low-level mold temperature. The recommended parameters are used in the simulation testing conducted with Moldflow software. Fig. 7 presents the results of warpage analysis given the recommended process parameters. The extent of warpage measures 2.919 mm, which is less than the experimental value obtained from the 27 experiments. Therefore, the Taguchi method can quickly determine appropriate process parameters and assist in reducing tryout time.

3.3 Curve analysis to optimize packing

As per the analysis above, packing pressure exerts the strongest effect on warpage out of all the other factors. In other words, warpage degree is more sensitive to changes in packing state than to changes in other factors. According to Computer-aided engineering (CAE) analysis, uneven volume contraction is the main cause of some instances of warpage. Unequal volume shrinkage can also be improved by controlling the packing process, thereby reducing warpage degree. Theoretically, if packing pressure changes with cooling time to consistently shrink the volumes of all parts, then the warpage degree of these parts decreases. By contrast, several of

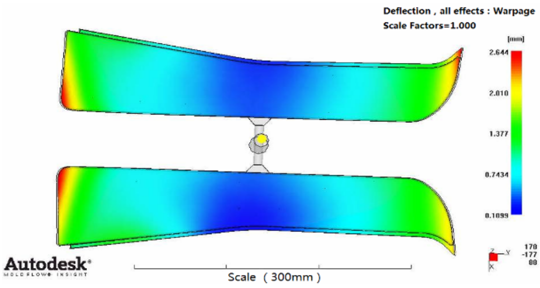


Fig. 8. Warpage under the optimal packing condition.

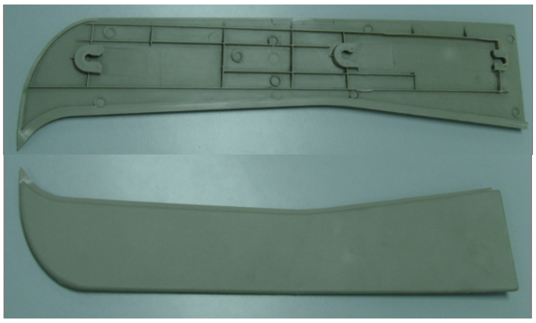


Fig. 9. Image of the product.

the simulations in the experiment follow the segmented gradient curve of packing pressure (0 s, 100%; 14 s, 100%; 15 s, 0%). Fig. 8 shows the result of the CAE analysis of warping given the recommended packing curve. The amount of warpage measures 2.644 mm, and the extent of warpage deformation is 0.27 mm smaller than that obtained with the recommended process parameters. Therefore, the extent of warpage on parts can be reduced by optimizing the packing curve to improve the process of plastic injection mold packing. Fig. 9 shows the interior panels.

4. Conclusion

The influence of injection molding process parameters on warpage was determined using the Taguchi method and through FE analysis experiments. According to the results of numerical analyses and simulations, packing pressure exerted the strongest influence on the degree of warpage in the interior panels of automobiles, followed by melt temperature, packing time, V/P conversion points, injection time, and mold temperature. Increasing packing pressure, improving melt temperature, extending the injection and packing times, and other measures help limit the extent of warpage. Otherwise, changing the mold temperature hardly affects warpage degree. According to the results of warpage analysis given the recommended process parameters, the extent of warpage is 2.919 mm, which is less than the value obtained from the 27 experiments. Furthermore, uniform volume contraction can be achieved by optimizing the packing profile. The warpage extent following packing curve optimization is 2.664 mm, which is less than the amount of warpage obtained under the recommended process parameters.

Acknowledgements

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