Effects of Injection Process Parameters on the Warpage of Thin-walled Plastic Parts

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The objective of this paper consists in the minimization of warpage problems which depend on the process parameters during injection molding of thin wall plastic parts using an optimization technique involving Taguchi method, S/N ratio and ANOVA method. For this purpose, a number of experiments are carried out by utilizing the combination of process parameters based on a three-level L_9 Taguchi orthogonal array table. To achieve the minimum warpage, the optimum level of process parameters is determined. A drain with 8 sockets is investigated, where melt temperature, mold temperature, injection speed, and packing pressure are selected to be the process variables. The results show that the optimum parameters that can minimize the warpage problem are: melt temperature (190°C), mold temperature (30°C), injection speed (70 mm/s), and packing pressure (55 MPa). The most effective factor on the warpage is packing pressure with a general influence of 55.71%.

Keywords: plastic injection molding; thin wall parts; warpage; Taguchi method; S/N ratio; ANOVA method; optimization

At world wide scale the plastic injection molding process occupies the second place after film extrusion with about 30% of the total plastic manufacture. The procedure of injection molding consists in the following steps: plasticizing, filling, packing, cooling and ejection of plastic part. The characteristics of injected products are highly unpredictable because the rheological behaviour of polymers is complicated. The desired combination of process parameters is generally acquired by an extended accumulation of experiences from the operators [1]. Defects of the products, such as warpage, shrinkage, sink marks, weld lines, air traps, residual stress etc. are caused by many factors during the production process. These defects influence the quality and accuracy of the products. Decreasing warpage is a very significant aspect involved in improving the quality of injection molded parts. The main causes that lead to warpage are: the rheological properties of the material and the design of the plastic part, the process conditions, non-uniform temperature, etc. Minimization of warpage is one of the top priorities to improve the quality of injection molded parts. Several studies brought some results on the optimization of process parameters [2-9]. The researchers have examined the influence of packing pressure, mold temperature, melt temperature, packing time, cooling time, runner type, and gate location on warpage of a thin wall plastic part that organizes the washing programs, run as the detergent system and a child guard [2]. The effects of process parameters for thin wall plastic parts were exploited using design of experiment (DOE), Taguchi orthogonal array, and finite element (FE) software MoldFlow. Their study also used a genetic algorithm (GA) to reduce the warpage. They have reached the most important process parameters (packing pressure, mold temperature, melt temperature, packing time, cooling time) using artificial neural network methodology (ANN) to reduce the computational cost of the optimization process. Their study shows that packing pressure, mold temperature, melt temperature, packing time, cooling time, runner type, and gate location influence warpage by 33.7, 21.6, 20.5, 16.1, 5.1, 1.5, and 1.3%, respectively. After parameters values were changed, the warpage was improved by about 51%. Tang et al. [5] have studied warpage of a thin wall plastic part using the Taguchi experimental design approach and found optimum parameters that can minimize the warpage defect: melt temperature (240°C), filling time (0.5 s), packing pressure (90%) and packing time (0.6 s). Among these factors, the melt temperature is the most effective factor and the filling time is not a significant factor. Using MoldFlow analyses and design of experiments (DOE), it was investigated the influence of injection molding process parameters in the study of minimizing warpage of a thin wall plastic part [9]. The results show optimum combination of process parameters: melt temperature (329.96°C), mold temperature (129.65°C), injection speed (75.19%), and packing pressure (49.99 MPa) for the simulation process, and melt temperature (330°C), mold temperature (121.17°C), injection speed (81.48%) and packing pressure (50 MPa) for experiments.

In this study, efficient minimization of warpage on a thin wall polypropylene part is investigated using the Taguchi experimental design, S/N ratio and the ANOVA approach. Three levels of melt temperature, mold temperature, injection speed, and packing pressure are selected to be the process variables in determination of warpage of the longitudinal edge. An 8-socket drain model is considered as an example of a thin wall plastic part. A simplistic scheme is used to reduce the number of experiments using Taguchi L_9 array.

This study has several key steps. The geometry of the plastic parts was drawn into a CAD program. The obtained model was imported into an FE program to be analyzed. A simplifying scheme using Taguchi orthogonal array (L_9) was chosen because it is suitable for 4 factors with 3 levels. Injection of the plastic part is made on a horizontal injection molding machine model SK 1600-810 and warpage is measured on an optical machine model HE400 from Starrett Precision Optical Ltd. The optimization procedure involves S/N ratio and ANOVA analysis which yield optimal levels of the parameters. At the end of this paper the study presentsthe results and discussions.

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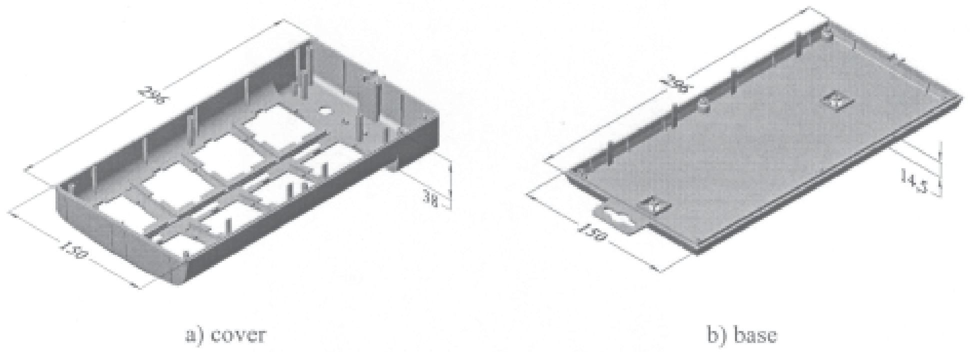
Properties	Parameters
Solid density (g/cm^3)	0.9
Melt Mass-Flow Rate (MFR) (230°C; 2,16 kg)	21.6
Tensile Stress (Yield; 23°C; Injection Molded) (MPa)	34.26
Tensile Strain (Yield; 23°C; Injection Molded) (%)	9.18
Notched Izod Impact Strength (23°C) (kJ/m^2)	2.77
Flexural Modulus – Secant (23°C; Injection Molded) (MPa)	1337

Table 1
STANDARD SPECIFICATION OF MIDILENA III J900 POLYPROPYLENE



a) cover b) base

Fig. 1. 3D geometry of the parts (all dimensions in mm)

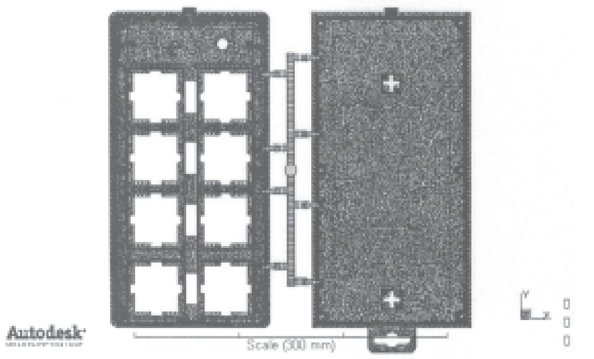


Fig. 2. Mesh for finite element analysis

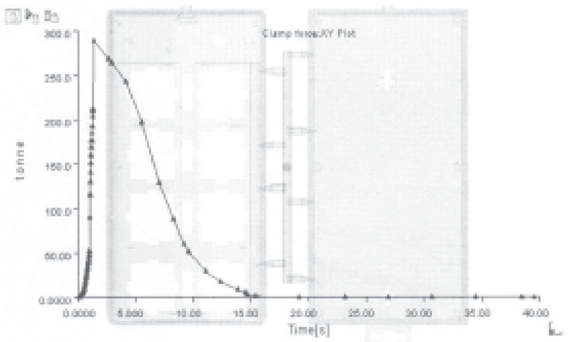


Fig. 3. Clamp force: XY Plot

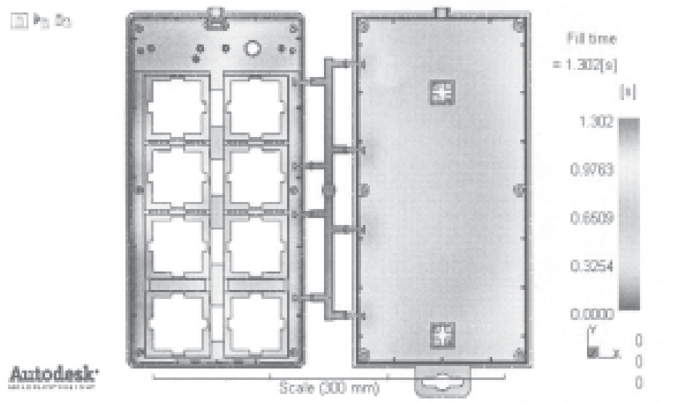


Fig. 4. Fill time

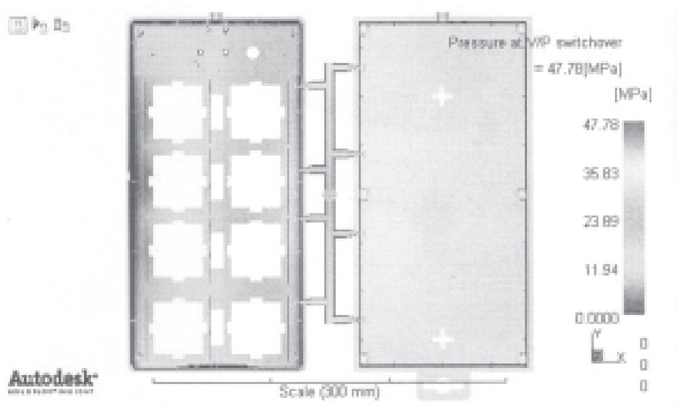


Fig. 5. Pressure at V/P switchover

Experimental part

Experimental material

In this study a thermoplastic polypropylene (PP) grade Midilena III J900 supplied by Rompetrol Petrochemicals was used. This material was chosen because of its widespread use in electrical drain manufacturing industry. The standard specifications of this material extracted from the analysis report are presented in table 1 [10].

Finite element analysis

The purpose of finite element analysis is to determine the range of experimental parameters by use of which: 1) parts obtained without short shot problems and with acceptable deformations; 2) diminished of the time for setting up the injection machine; 3) material economy is achieved.

The experimental plastic part investigated is a drain with 8 sockets. This drain is a thin wall part made of two pieces. The solid model of the part was generated into a CAD software (fig.1). The cover dimensions of the solid model (the left one) are 269 mm × 150 mm × 38 mm and the base dimensions (the right one) are 269 mm × 150 mm × 14.5 mm. The material properties required for the finite element analysis were extracted from the software database such that they match with the properties of the material used in the experiment (melt mass-flow rate, solid density and flexural modulus).

Finite element analysis of injection molding parameters was performed using Autodesk Moldflow Insight 2011 Software. The solid model was imported from Moldflow and it was dual domain meshed with 107827 triangular elements, 53970 nodes, 12 layers in the gap-wise direction while the runner system was modeled with 213 beam elements (fig. 2). The match percentage is 89.7%, the reciprocal percentage is 89.2 % and the average aspect ratio is 2.65. It should be noted that to achieve accurate results it is recommended that match percentage and reciprocal match percentage to be minimum 85%. The part volume to be filled is 241.476 cm^3, the runner system volume to be filled is 18.698 cm^3, and the total projected area is 746.773 cm^2.

For the finite element analysis the following parameters were chosen: mold surface temperature of 40°C, melt temperature of 190°C, filling control profile was achieve using absolute ram speed by ram speed vs. ram position configuration, velocity by injection pressure at 75 MPa, packing control profile (%) of filling pressure vs. time, and cooling time was 25 s.

Based on the finite element analysis results, the injection molding parameters were estimated. Figure 3 presented the clamp force (≈ 300 t), filling time distribution (1.3 s) is pointed in figure 4, while maximum pressure at V/P switch over (≈ 48 MPa) is showed in figure 5. Volumetric shrinkage at ejection (≈ 11%) is displayed in figure 6, and the variation of pressure at the injection location in figure 7. From figure 7 we also could estimate the total injection time, about 42 s.

The parameters extracted from the numerical simulation were used to adjust the injection molding machine, we ensured against short shot problems, and we were able to set the level of the range for the factors that we want to study.

Experimental setup

Based on the finite element analysis of the injection molding the following parameters are chosen to be studied: melt temperature (i.e. A (180; 190; 200°C)), mold temperature (i.e. B (30; 40; 50°C)), injection speed (i.e. C (70; 90; 110 mm/s)) and packing pressure (i.e. D (55; 60; 65 MPa)).

In order to reduce the number of experiments and to determine the most influent process parameter on the warpage, a simplistic Taguchi L_9 orthogonal array has been chosen because it is suitable for four factors (parameters) with three levels. Taguchi provided tables of orthogonal arrays to be used as statistical designs. Orthogonal arrays are highly desirable in the design of experiments because they possess many important statistical properties, such as the statistical independence of estimated factor effects [11]. The L_9 orthogonal array used in this study is shown in table 2.

Samples were injected on a horizontal injection molding machine model SK 1600-810 with clamping force of 1600 kN, screw diameter of 55 mm and maximum injection pressure of 180 MPa. Mold temperature control was achieved using a Tool-Temp equipment model TT180. Melt temperature setup configuration was controlled with 5 segments and the filling control was accomplished using absolute ram speed by ram speed vs. ram position configuration. Packing stage configuration was achieved by packing pressure vs. time. The cooling time of the thin wall plastic part was 25 s.

For every experimental line from Taguchi orthogonal array seven samples were injected.

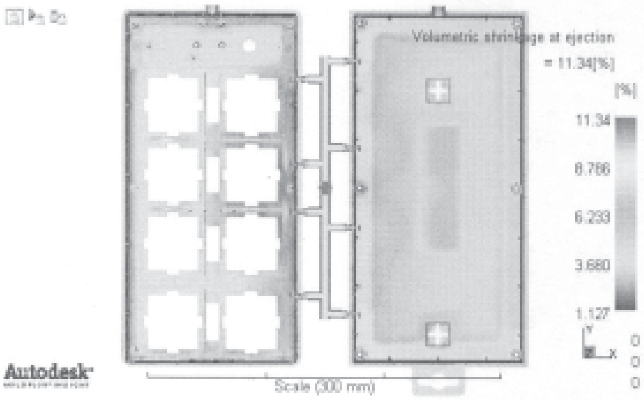


Fig. 6. Volumetric shrinkage at ejection

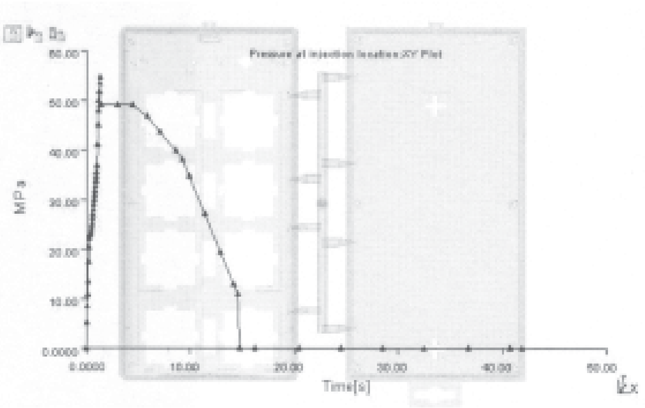


Fig. 7. Pressure at injection location: XY Plot

Table 2
L_9 ORTHOGONAL ARRAY

Trial no.	Control factor			
	Melt temperature A (°C)	Mold remperature B (°C)	Injection speed C (mm/s)	Packing pressure D (MPa)
1	180	30	70	55
2	180	40	90	60
3	180	50	110	65
4	190	30	90	65
5	190	40	110	55
6	190	50	70	60
7	200	30	110	60
8	200	40	70	65
9	200	50	90	55

Results and discussions

Warpage measurement

Figure 8 represents the experimental part. The marked areas show the edges where we are studying the warpage. Warpage measurements were performed on the longitudinal edges of the plastic parts 48 h after injection, with an optical machine HE400 from Starrett Precision Optical Ltd shown in figure 9. This machine has a

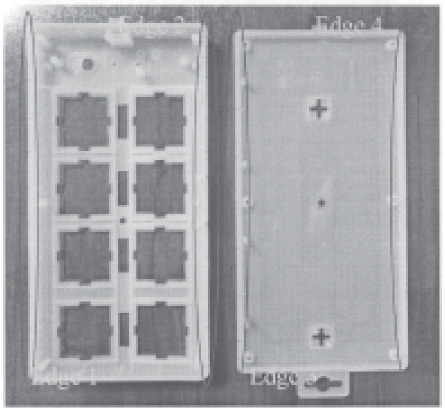


Fig. 8. The configuration of the part and longitudinal edges scheme zone

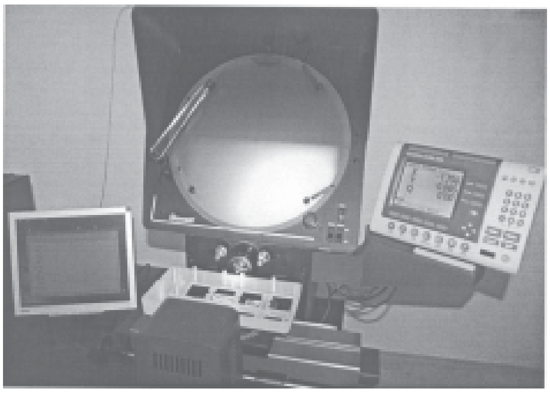
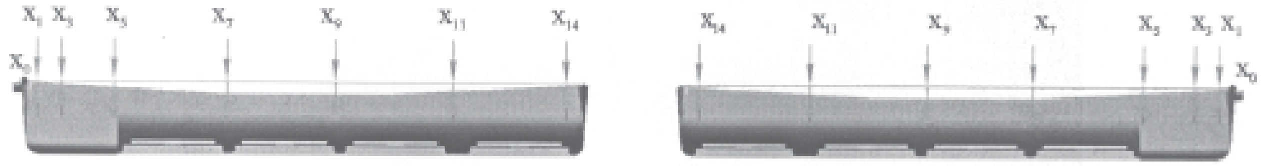


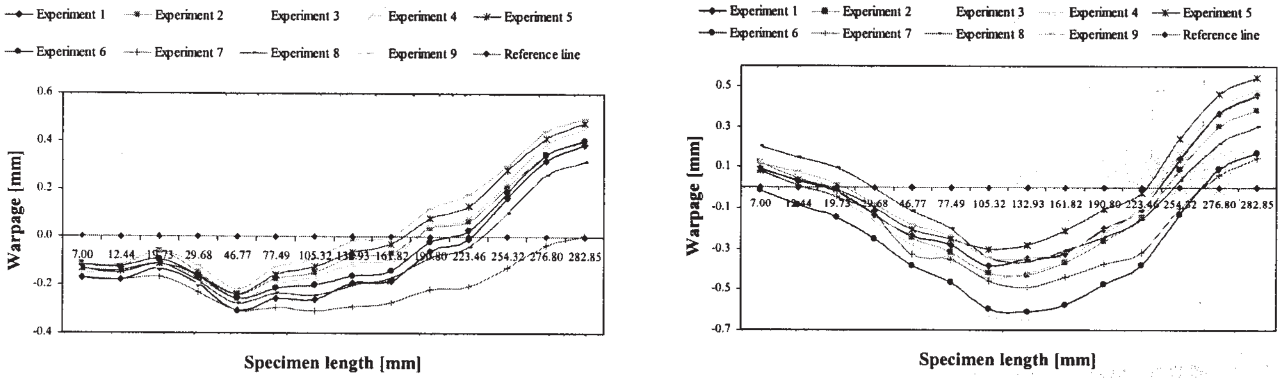
Fig. 9. Warpage measurement with optical machine equipment



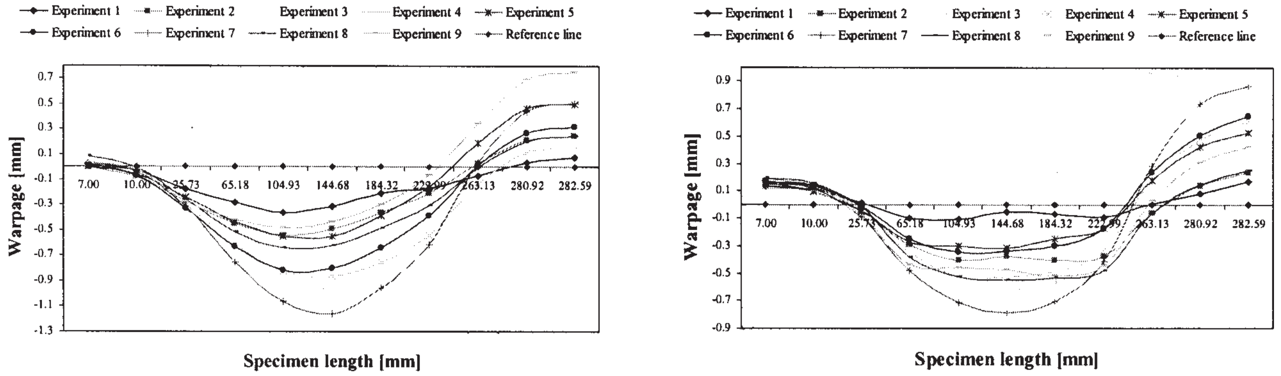
a. Edge 1 b. Edge 2

c. Edge 3 d. Edge 4

Fi. 10. Schematic measurement of warpage



a. Edge 1 **b.** Edge 2



c. Edge 3 **d.** Edge 4

Fig. 11. Cover and base part warpage

measurement accuracy of 1 μm and maximum measuring length of 254 mm x 100 mm. The points measured were related to a fixed point x_0 on the corner of the plastic part. They were compared with a reference line (the undistorted edge). Schematic measurement of the warpage is illustrated in figure 10. The x_i values ($i \in [1, 14]$) represent warpage of the measured points. The average warpage of the measurements on the longitudinal edges for each sample under study is pointed in figure 11. The statistic confidence interval was verified using MINITAB V16 software. The values outside the range were eliminated and P-Value should be more than 0.05. On the sole basis of the results presented in the diagrams, the experiment with the smallest warpage cannot be chosen, and the most influent parameter to warpage cannot be identified. This is why the results are further analysed with S/N ratio and the ANOVA method. In this way, the best set of parameters that generated minimum warpage can be established. Moreover, the contribution of each parameter influence to warpage can be found out as a percentage.

S/N ratio

The Taguchi technique uses the S/N ratio approach to measure and determine the quality characteristics of the parameters deviating from the desired value. In calculating the S/N ratio, "the smaller is better" quality characteristic was selected (eq 1).

Smaller is better,

$$\eta = -10\log(MSD) \qquad (1)$$

where

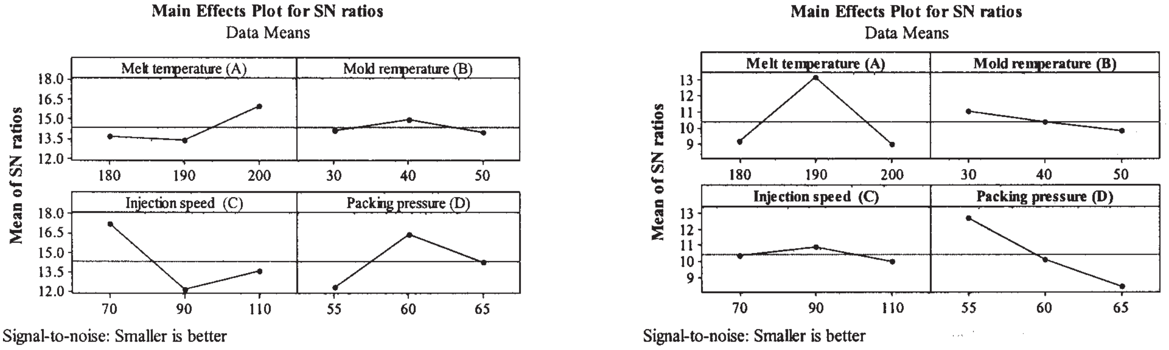
$$MSD = \frac{1}{n} \cdot \sum_{i=1}^{n} y_i^2 \qquad (2)$$

MSD is the mean square deviation, *y* the observation or data and *n* is the number of tests in a trial [11].

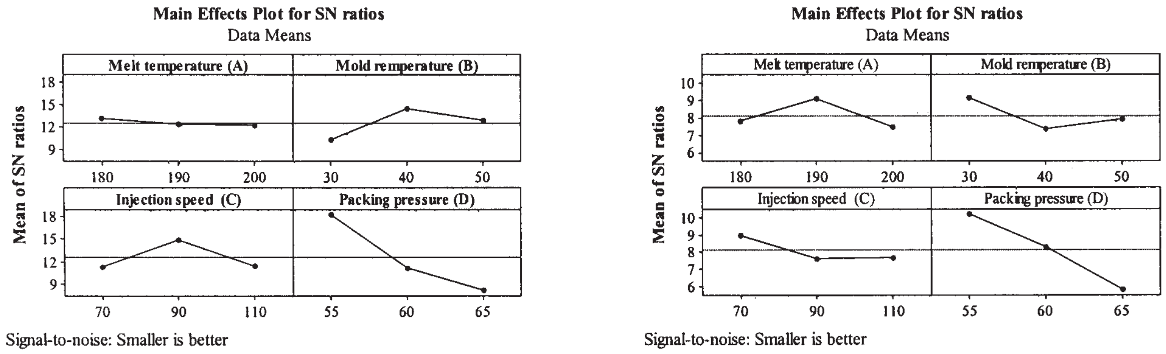
The S/N ratio analyses were done using MINITAB V16 software. Results for average warpage and S/N ratio are summarized in table 3. Based on the data in table 3, the S/N response diagram can be constructed as shown in figure 12.

Table 3
SUMMARIZE OF THE EXPERIMENTAL RESULTS

Trial no.	Average warpage for edge 1 (mm)	S/N ratio (dBi)	Average warpage for edge 2 (mm)	S/N Ratio (dBi)	Average warpage for edge 3 (mm)	S/N Ratio (dBi)	Average warpage for edge 4 (mm)	S/N Ratio (dBi)
1	0.192	14.338	0.252	11.972	0.172	15.289	0.255	11.861
2	0.195	14.185	0.343	9.294	0.157	16.082	0.460	6.737
3	0.240	12.396	0.494	6.126	0.399	7.981	0.573	4.840
4	0.286	10.879	0.244	12.252	0.399	7.981	0.431	7.305
5	0.275	11.224	0.177	15.041	0.113	18.938	0.317	9.977
6	0.126	17.972	0.245	12.217	0.317	9.979	0.319	9.924
7	0.141	17.022	0.362	8.826	0.426	7.412	0.384	8.303
8	0.106	19.455	0.457	6.802	0.379	8.427	0.547	5.236
9	0.268	11.432	0.276	11.182	0.091	20.819	0.360	8.874



a. Edge 1 **b.** Edge 2



c. Edge 3 **d.** Edge 4

Fig. 12. Parameters influence to warpage

Table 4
ANOVA TABLE FOR EDGE 1

Source	Dof	Seq SS	Adj MS	P(%)
Melt temperature (A)	2	5.03×10^{-3}	2.51×10^{-3}	13.67
Mold temperature (B)	2	0.59×10^{-3}	0.29×10^{-3}	1.63
Injection speed (C)	2	18.6×10^{-3}	9.3×10^{-3}	50.49
Packing pressure (D)	2	12.6×10^{-3}	6.3×10^{-3}	34.21
Pooled error	0	0	0	
Total	8	36.84×10^{-3}	18.42×10^{-3}	100

Table 5
ANOVA TABLE FOR EDGE 2

Source	Dof	S	V	P(%)
Melt temperature (A)	2	40.33×10^{-3}	20.17×10^{-3}	44.99
Mold temperature (B)	2	4.47×10^{-3}	2.24×10^{-3}	4.99
Injection speed (C)	2	4.82×10^{-3}	2.41×10^{-3}	5.38
Packing pressure (D)	2	40.02×10^{-3}	20.01×10^{-3}	44.64
Pooled error	0	0	0	
Total	8	89.65×10^{-3}		100

Table 6
ANOVA TABLE FOR EDGE 3

Source	Dof	S	V	P(%)
Melt temperature (A)	2	4.77×10^{-3}	2.38×10^{-3}	3.16
Mold temperature (B)	2	20.24×10^{-3}	10.12×10^{-3}	13.43
Injection speed (C)	2	15.38×10^{-3}	7.69×10^{-3}	10.21
Packing pressure (D)	2	110.32×10^{-3}	55.16×10^{-3}	73.20
Pooled error	0	0	0	
Total	8	150.71×10^{-3}		100

Table 7
ANOVA TABLE FOR EDGE 4

Source	Dof	S	V	P(%)
Melt temperature (A)	2	11.05×10^{-3}	5.53×10^{-3}	11.95
Mold temperature (B)	2	11.50×10^{-3}	5.75×10^{-3}	12.43
Injection speed (C)	2	4.47×10^{-3}	2.24×10^{-3}	4.84
Packing pressure (D)	2	65.45×10^{-3}	32.73×10^{-3}	70.78
Pooled error	0	0	0	
Total	8	92.48×10^{-3}		100

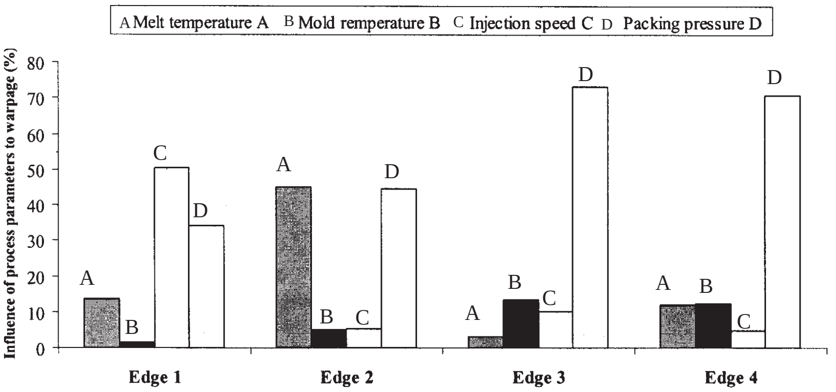


Fig. 13. Influence of molding parameters on the warpage

Table 8
BEST SET OF COMBINATION PARAMETERS

Parameter	Edge 1	Edge 2	Edge 3	Edge 4
Melt temperature (A)	3	2	1	2
Mold temperature (B)	2	1	2	1
Injection speed (C)	1	2	2	1
Packing pressure (D)	2	1	1	1

ANOVA method

The aim of the analysis of variance ANOVA is to find out the ratios percentage affecting process parameters on the warpage problem. For this study, the percentages of process parameters contribution for minimum warpage are shown in tables 4-7. The results of the analyses of process parameters influence are plotted into a diagram shown in figure 13. From the graphic we can see that the most important parameter to warpage is packing pressure with an astonishing influence of 70% to the base and 40% to the cover. The influence of melt temperature on warpage of the base part (10%) is less than on the cover part (40%) because of the simple geometrical shape of the base compared with the complex geometry of the cover and of the flow front path. Injection speed has a powerful influence on warpage for edge 1 because this edge is on the other side of the supply network, and also because of the complexity of the cover part. Mold temperature has the least influence on warpage, about 10%. The best set of combination parameters which yielded minimum warpage is determined by selecting the highest value of each level. Thus, we obtain four results, one for each edge, as we can see in table 8.

Since we had to choose only one level for each parameter generating minimum warpage, by using S/N ratio and ANOVA method we established the optimum level as: A_2 (190°C), B_1 (30°C), C_1 (70mm/s) and D_1 (55MPa).

Conclusions

In this study, an optimization methodology using L_9 Taguchi orthogonal array, S/N ratio and ANOVA method was introduced to minimize warpage of a thin wall plastic part manufactured by injection molding. The purpose of this study was to determine the optimal values of the injection parameters that determine samples with high quality. High quality samples have been defined as parts with minimal warpage and the least possible number of aspect problems. To achieve minimum warpage, the optimum process levels of parameters are determined. As an example, a drain with 8 sockets is investigated, where melt temperature, mold temperature, injection speed, and packing pressure are selected to be the process variables.

The experimental facilities of this study are an injection molding machine model SK 1600-810, a thermostatic equipment – Tool-Temp model TT180, and an optical machine HE400. After the optimization, the best set of parameter combination determining minimum warpage is: melt temperature (190°C), mold temperature (30°C), injection speed (70 mm/s) and packing pressure (55 MPa). The most important factor on warpage is packing pressure with a general influence of 55.71%. Melt temperature and injection speed are also important to warpage but mold temperature has a minor influence. Taguchi orthogonal array, S/N ratio and ANOVA method are very powerful tools to solve warpage problems and can be successfully employed to improve injection molding of other thin wall plastic parts with complex geometry.

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