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Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part

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Abstract

This paper deals with the application of Taguchi optimization technique to reduce warpage problem related to the shrinkage variation depended on process parameters during production of thin-shell plastic components for orthose part. For this purpose, a number of MoldFlow analyses are carried out by utilizing the combination of process parameters based on three-level of L_{27} and L_9 Taguchi orthogonal design. The signal-to-noise (S/N) and the analysis of variance (ANOVA) are used to find the optimum levels and to indicate the impact of the process parameters on warpage and shrinkage. The results show that warpage and shrinkage are improved by about 2.17% and 0.7%. A verification test is also performed to prove the effectiveness of Taguchi technique after the optimum levels of process parameters are determined. It can be clearly inferred from this conclusion that Taguchi optimization is sufficient to solve the warpage problem with shrinkage for thin-shell plastic components of orthose part.

Keywords: Design of experiment; Plastic injection molding; Taguchi optimization technique; The S/N ratio; Analysis of variance; Shrinkage; Warpage

1. Introduction

Plastic injection molding is one of the most important methods applied for forming thin-shell plastic products in industry. Plastic injection molding (PIM) has also some advantages such as short product cycles, high quality part surfaces, good mechanical properties, low cost, and light weight, so it is becoming increasingly more significant in today's plastic production industries. PIM needs to be improved because of all reasons mentioned and the customer demands. The process of PIM can be summarized shortly: the polymer material is heated to its melting temperature. The melted polymer is injected into the cavity by a gate under high pressure, below the freezing temperature of the polymer. When filling is nearly completed, the cavity is kept at a constant pressure for the packing pressure. Packing pressure is utilized to fill the remaining volume of the cavity and to reduce the shrinkage due to cooling. If cools down, the shrinkage occurs in the cavity. When the inner of the cavity is stable case, the plastic product is extracted from the mold [1].

The quality of plastic injection molding parts depends on the material, part and mold designs, and the process parameters required to manufacture them. Warpage and shrinkage involve among the most highly the defects of thin-shell plastic parts in terms of the quality. The reasons of warpage in plastic injection molded parts are very complex and numerous. The main cause of warpage is commonly known as the variation in shrinkage towards injection process of thin-shell plastic parts. Material properties, part design, and injection-molding process conditions are classified as the factors influencing the variations in the part shrinkage during injection molded thin-shell parts [2]. Part geometry and mechanical property of material also play a critical role in the warpage and the final warpage of part considerably bases on its mechanical

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stiffness, which is a function of the geometrical configuration and the material's mechanical properties. If a part has higher mechanical stiffness, it is subjected to warp the low due to high variations in the shrinkage and the part with less mechanical stiffness will be more warp [3].

On the other hand, three main reasons of shrinkage affecting greatly warpage are introduced as follows: Flow orientation: it is reveal to directional shrinkage variations; Area shrinkage: it causes from packing pressure and variation in local crystallization. It is widespreadly accepted that semicrystalline plastics shrink more than amorphous ones because of the closer packing of the crystalline structure [4]. Differential cooling: it will result in variations in sectional shrinkage. The temperature difference between the upper and lower surfaces will cause differential shrinkage between cavity and core. This shrinkage difference will produce a bending moment after part is extracted from mold. This bending moment cause either warpage or residual stress depending on the mechanical stiffness of part [1,3].

Some researches have been performed to optimize the optimum levels of process parameters based on orthogonal array experiment of Taguchi's throughout injection molding of plastic components. Chen and Shiou [5] have studied for determining the optimal process parameters depended on Taguchi orthogonal array in finish operation of a free-form surface plastic injection molding. Ghani et al. [6] describes the Taguchi optimization methodology to find a combination of milling parameters by using the *S*/*N* ratio approach and analysis of variance. Lin [7] has examined to present the effectiveness of Taguchi technique with multiple performance characteristics by employing cutting parameters. Tseng [8] used to a statistical two-level, 16 run factorial experiments to evaluate the influence of various process parameters on the dimensional variation of injection-molded ceramic.

In this study, orthogonal array experiment of L_{27} and L_9 were created to find the optimum levels of process parameters and to determine the impacts of those towards production of thin-shell plastic components for orthose part exploiting the *S*/*N* ratio and ANOVA.

2. Description of Taguchi technique

Taguchi techniques were developed by Taguchi and Konishi [9]; these techniques have been utilized widely in engineering analysis to optimize the performance characteristics within the combination of design parameters. Taguchi technique is also power tool for the design of high quality systems. It introduces an integrated approach that is simple and efficient to find the best range of designs for quality, performance, and computational cost [10].

In Taguchi technique, three-stages such as system design, parameter design, and tolerance design are employed. System design consists of the usage of scientific and engineering information required for producing a part. Tolerance design is employed to determine and to analyse tolerances about the optimum combinations suggested by parameter design. Parameter design is used to obtain the optimum levels of process parameters for developing the quality characteristics and to determine the product parameter values depending optimum process parameter values [11]. In this study, parameter design is coupled to achieve the optimum levels of process parameters leading to minimum warpage and shrinkage during the manufacturing of thin-shell plastic parts.

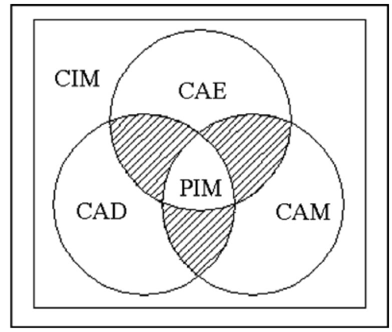

Fig. 1. Production of vicious circle for plastic parts.

Based on orthogonal arrays, the number of experiments which may cause to increase the time and cost can be reduced by using Taguchi technique. It employs a special design of orthogonal arrays to learn the whole parameters space with a small number of experiments only. Taguchi offers the use of the *S*/*N* ratio to identify the quality characteristics applied for engineering design problems. The *S*/*N* ratio characteristics can be divided into three steps: the smaller the better, the nominal the best, and the larger the better, signed type [12]. In this study, the smaller the better quality characteristic is chosen to solve warpage problem with shrinkage variation through the optimal levels of process parameters.

A statically analysis of variance (ANOVA) can be utilized to present the influence of process parameters on warpage and shrinkage. In this way, the optimum levels of process parameters can be predicted. Production of vicious circle for plastic parts is shown in Fig. 1. The details of the *S*/*N* ratio and ANOVA analyses are discussed in the following sections.

3. Experimental set-up

3.1. Tool and material

A series of milling operations were conducted to manufacture the mold components used in injecting of thin-shell plastic components for orthose part on a DECKEL MAHO five axis CNC milling machine. Milling operations were performed in a block with dimensions of 100 mm × 100 mm × 50 mm. The workpiece material was Aluminum 7075-T6 that had chemical properties of 1.6 Cu, 2.5 Mg, 0.23 Cr, and 5.40 Zinc. The material hardness was found to be 150 BHN. Cutting tools was the diameter of 10 mm flat and mill and it's material PVD Al–TiN

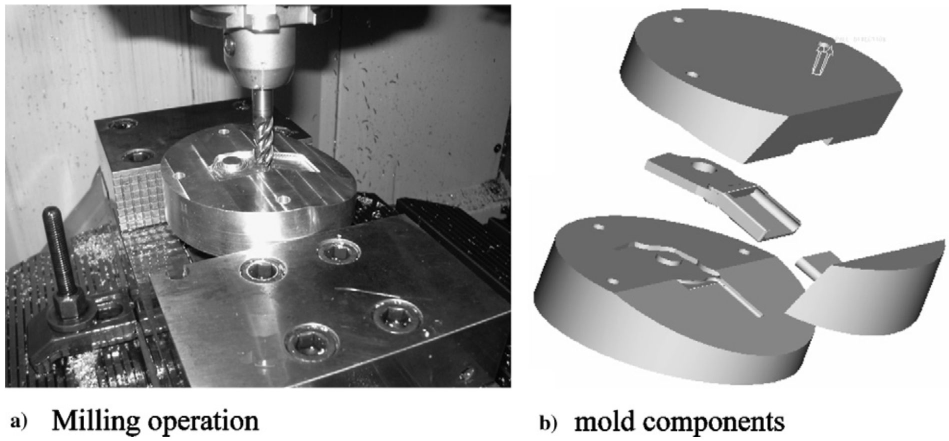

Fig. 2. The milling operation and all of the mold components.

coated solid carbide fabricated by Sandvik Coromont. The milling operation applied for one of mold components and all of mold components are illustrated in Fig. 2a and b.

3.2. Orthogonal array experiment

Taguchi's orthogonal arrays were used in engineering analysis and they consist of the ranges of plastic injection molding process parameters based on three-level design of experiments. Firstly, L_{27} orthogonal array was created for 27 finite element (FE) analyses of orthose part by utilizing five process parameters such as material flow rate (M_{FR}), injection velocity (I_v), mold temperature (MoT), and melt temperature (MeT) corresponding to injection time (I_t) parameter. Secondly, L_9 orthogonal was created for 9 finite element (FE) analyses of orthose part by using four process parameters including injection time (I_t), packing pressure (P_P), packing pressure time (P_{PT}), and cooling time (C_T) corresponding to warpage and shrinkage parameters. The ranges of five process parameters and four process parameters are given in Tables 1 and 2.

While determining of the value ranges of process parameters including injection velocity (I_v), material flow rate (M_{FR}), mold temperature (MoT), and melt temperature (MeT), the optimal values recommended by MoldFlow material library were considered. The other proces parameters were selected by exploiting the experiences in plastic injection molding industry. In Table 2, "*a*" and "*c*" values are the maximum and minimum of injection time values in Table 3 and "*b*" value is calculated as $b = (a + c)/2$. Injection time values obtained during 27 FE analyses of orthose part are listed in Table 3.

Table 1
The ranges of five process parameters

M_{FR} (g/10 min)	I_V (cm/s)	MoT (°C)	MeT (°C)	I_P (MPa)
8-12-16	130-142.5-156.4	50-75-100	230-265-300	8-12-16

Table 2
The ranges of four process parameters

I_t (s)	P_P (MPa)	P_{PT} (s)	C_T (s)
a-b-c	16-21-26	4-6-8	12-15-18

3.3. Plastic injection molding

The mold parts were designed and manufactured to inject thin-shell plastic components of orthose that is widely utilized in biomedical applications for paralysis patients. Orthose is mounted the side of kneecap region in humans's leg and it also helps hold human's leg in stable

Table 3
L_{27} (3^5) orthogonal array of Taguchi

M_{FR} (g/10 min)	I_V (cm/s)	MoT (°C)	MeT (°C)	I_P (MPa)	I_t (s)
1	1	1	1	1	**2.1050**
1	1	1	1	2	1.6980
1	1	1	1	3	1.3450
1	2	2	2	1	1.1250
1	2	2	2	2	1.1200
1	2	2	2	3	1.1150
1	3	3	3	1	1.0160
1	3	3	3	2	1.0100
1	3	3	3	3	1.0060
2	1	2	3	1	0.8186
2	1	2	3	2	0.8145
2	1	2	3	3	**0.8125**
2	2	3	1	1	2.0750
2	2	3	1	2	1.9940
2	2	3	1	3	1.9630
2	3	1	2	1	1.0280
2	3	1	2	2	0.9166
2	3	1	2	3	0.9019
3	1	3	2	1	1.2425
3	1	3	2	2	1.2220
3	1	3	2	3	1.2100
3	2	1	3	1	0.8188
3	2	1	3	2	0.8158
3	2	1	3	3	0.8137
3	3	2	1	1	2.0960
3	3	2	1	2	1.9010
3	3	2	1	3	1.5470

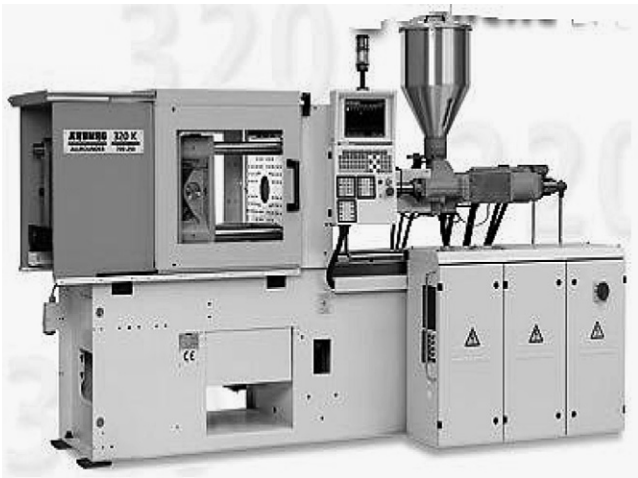

Fig. 3. Plastic injection molding machine.

position during take a walk. Orthose is equipped with the elements that are made of aluminum bars in dimensions of 20 mm × 10 mm × 300 mm. In this study, the second component of orthose was prefered as FE model and plastic injected part. The plastic components of orthose were injected in ARBURG (during the experiment stage, a horizontal plastic injection machine tool produced by ARBURG) plastic injection machine. The technical details of the injection machine are closing force (200 ton), maximum injection pressure (100–120 MPa), screw pressure time (0.02 s), and shot size (0.02 kg), respectively. Plastic injection molding machine used in this study is represented in Fig. 3.

3.3.1. Finite element (FE) model of orthose part

FE analysis of orthose part is performed using MoldFlow plastic insight software (MPI) [13]. The orthose part has width, length, and height of 25.59 mm, 54.04 mm, and 14.21, consecutively. Geometry of orthose part employed in this current study was shown in Fig. 4a. Orthose part is made of PC/ABS CMOLD generic estimates and its material properties are given in Table 4. FE model of orthose part is created by discritizing the geometry into smaller simple elements. The FE model shown in Fig. 4b includes 8030 tetrahedron elements.

Table 4
Material properties of PC/ABS

Melt density (gr/cm3)	1.0063
Mold temperature (°C)	75
Melt temperature (°C)	265
Viscosity (Pa s)	VI(300)102
Poisson rate	0.38
Material structure	Amorphous

4. Analysis of experimental data

4.1. Conceptual S/N ratio approach

Taguchi technique utilizes the S/N ratio approach to measure the quality characteristic deviating from the desired value. It is also used the S/N ratio approach instead of the average value to convert the experimental results into a value for the evaluation characteristic in the optimum parameter analysis. The S/N ratio is quoted in dBi units and it can be defined as:

$$\eta = -10\log(\text{M.S.D.}), \tag{1}$$

where M.S.D. is the mean-square deviation for the output characteristic. The S/N ratio characteristics can be divided into three stages: the nominal-the better, the smaller-the better, and the higher-the better when the quality characteristics are continuous for engineering analysis [12,14]. Since the objective of this study is to reduce the warpage problem with the shrinkage through optimum process parameters in plastic injection molding, the smaller-the better quality characteristic is employed in this study. The M.S.D. for the smaller-the better quality characteristic can be expressed as:

$$\text{M.S.D.} = \frac{1}{N}\left(\sum_{i=1}^{n} Y_i^2\right), \tag{2}$$

where Y_i is the value of warpage and shrinkage for the ith test. n is the number of tests and N is the total number of data points. Because −log is a monotone decreasing function, it implies that we should maximize the S/N value. So, the S/N values are calculated by exploiting Eqs. (1) and (2). Warpage and shrinkage values under the process parameters corresponding injection time (I_t), packing pres-

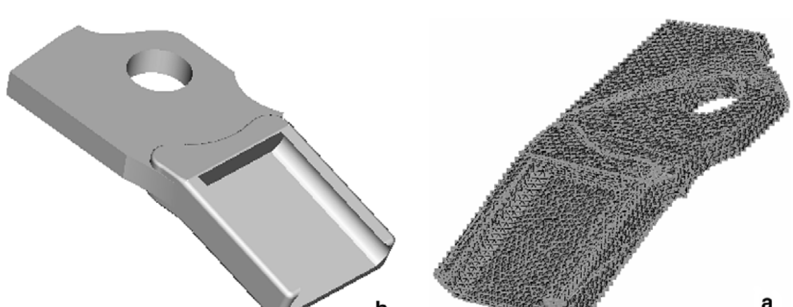

Fig. 4. The geometric and FE model of orthose part.

Table 5
The warpage-shrinkage and their S/N ratio values (L_9 3^4)

Set No.	I_t (s)	P_P (MPa)	P_{PT} (s)	C_T (s)	Warpage (mm)	Shrinkage (%)	S/N ratio values for warpage (dBi)	S/N ratio values for shrinkage (dBi)
1	1	1	1	1	0.457	6.300	+6.802	−15.99
2	1	2	2	2	0.439	5.240	+7.151	−14.39
3	1	3	3	3	0.421	4.910	+7.514	−13.82
4	2	1	2	3	0.428	5.440	+7.371	−14.71
5	2	2	3	1	0.414	5.034	+7.660	−14.04
6	2	3	1	2	0.418	6.340	+7.576	−16.04
7	3	1	3	2	0.432	5.414	+7.290	−14.67
8	3	2	1	3	0.425	5.964	+7.432	−15.51
9	3	3	2	1	0.419	4.937	+7.556	−13.87

sure (P_p), packing pressure time (P_{PT}), and cooling time (C_T) based on L_9 orthogonal array of Taguchi and their S/N ratio values are listed in Table 5.

Warpage and shrinkage response table for each process parameters at the levels of 1, 2, and 3 were created by utilizing the S/N ratio values for warpage and shrinkage in the two left columns. The values obtained this process are recorded in Table 6. On the other hand, the same procedure required for building of the S/N ratio response table including four process parameters was applied and the S/N response values are recorded in Table 7.

In order to find the optimum levels of four parameters, Fig. 5 is drawn exploiting S/N response table for warpage and shrinkage. It is also seen from Fig. 5 that the maximum S/N response value at each level has given the minimum warpage and shrinkage.

Table 6
Response values table

Process parameters	Warpage (mm)				Shrinkage (%)			
	I_t	P_P	P_{PT}	C_T	I_t	P_P	P_{PT}	C_T
Levels	1	1	1	1	2	1	1	2
Values	0.426	0.426	0.420	0.417	5.159	5.272	5.755	5.219

Table 7
S/N response values table

Process parameters	Warpage (mm)				Shrinkage (%)			
	I_t	P_P	P_{PT}	C_T	I_t	P_P	P_{PT}	C_T
Levels	2	3	3	3	2	1	1	2
Values	+6.957	+6.980	+6.916	+6.854	−14.23	−14.41	−15.11	−14.32

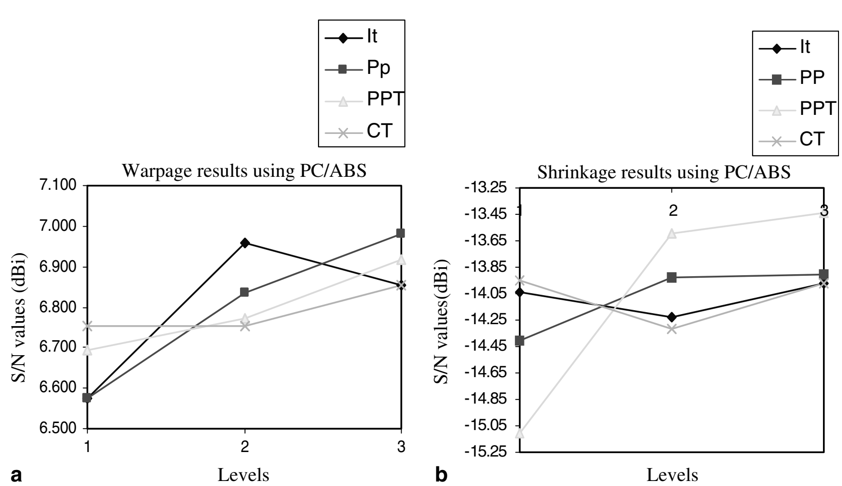

Fig. 5. Plots of process parameters effects for warpage and shrinkage with PC/ABS.

Table 8
ANOVA results for warpage and shrinkage

	Warpage (mm)				Shrinkage (%)			
	I_t	P_P	P_{PT}	C_T	I_t	P_P	P_{PT}	C_T
Sum of sq. (s)	1.691	3.19	2.169	0.375	0.554	0.846	5.82	0.281
Variance (V)	0.85	2.093	1.008	0.16	0.29	0.425	3.627	0.145
F ratio (F)	59200	160532	78009	11050	20015	29389	307235	9899
P value (P)	0.0003	0.0001	0.0002	0.0015	0.0009	0.0006	0.0001	0.0021
Percent (%)	15.17	58.03	23.03	3.68	5.528	7.830	84.054	2.588

4.2. Analysis of variance (ANOVA)

The aim of the analysis of variance is to evaluate the significance of process parameters on warpage and shrinkage for this paper. If some process parameters do not considerably impact warpage and shrinkage, they can be kept in the recommended values of mold analyser and excluded in building of prediction model and Taguchi optimization process.

In this way, the efficient optimization process has been procuded. For this paper, the percentage contribution of variance can be calculated as depended on the following equations. Here, the total sum of squared deviations SS_T from the total mean S/N ratio η_n can be introduced as [10]:

$$SS_T = SS_d + SS_e, \tag{3}$$

$$SS_T = \sum_{i=1}^{n_i} (\eta_i - \eta_n)^2, \tag{4}$$

where n_i is the number of experiments in the orthogonal array and η_i is the mean S/N ratio for the ith experiment. The percentage contribution ρ can be calculated as follow:

$$\rho = \frac{SS_d}{SS_T}, \tag{5}$$

where SS_d is the sum of squared deviations and SS_e is the sum of squared error. The results from ANOVA are shown in Table 8. F ratio corresponding 95% confidence level in calculation of four process parameters analysed from MoldFlow accurately is $F_{0.05,2,8} = 4.459$. It can also be calculated from the ratio of the mean sum of squared deviations. P value reports the significance level and the percent (%) depicts the significance rate of parameters on warpage and shrinkage in Table 8. It can be observed from Table 8 that packing pressure (P_P), packing pressure time (P_{PT}), injection time (I_t), and cooling time (C_T) influence warpage by 58.03%, 23.03%, 15.17%, 3.68% and shrinkage by 7.83%, 84.054%, 5.528%, 2.588% for polymer material of PC/ABS, respectively. Each of percent numbers in Table 8 shows that four process parameters have different importance on warpage and shrinkage.

5. Determination of the minimum warpage and shrinkage

By using the optimal levels of parameters process in Table 6 (response values table for warpage and shrinkage), the minimum warpage and shrinkage were estimated as based on Eqs. 6a(a) and 6b(b) for producing plastic orthose part with polymeric material PC/ABS. Due to the all of these parameters have a very strong effect on warpage and shrinkage, they are employed to calculate the minimum warpage and shrinkage

$$\begin{aligned} \text{Minimum warpage} & \\ &= I_{t1} + P_{P1} + P_{PT1} + C_{T1} - 3 \times (\overline{Y_i}) \qquad (6a) \\ &= 0.426 + 0.426 + 0.420 + 0.417 - 3 \times (0.428) \\ &= 1.689 - 1.284 = 0.405 \text{ mm} \end{aligned}$$

$$\begin{aligned} \text{Minimum shrinkage} & \\ &= I_{t2} + P_{P1} + P_{PT1} + C_{T2} - 3 \times (\overline{Y_i}) \qquad (6b) \\ &= 5.159 + 5.272 + 5.755 + 5.219 - 3 \times (5.509) \\ &= 21.405 - 16.527 = 4.878 \ (\%) \end{aligned}$$

In similar way, the maximum S/N ratio is calculated to control whether or not the minimum warpage and shrinkage is appropriate. The maximum S/N ratio for warpage and shrinkage was predicted as based on Eqs. (7a) and 7b(b). The maximum S/N ratio for warpage and shrinkage varies from the min = +5.591 dBi to $+\infty$ dBi and from min = −15.11 dBi to $+\infty$ dBi, consecutively.

$$\begin{aligned} \text{Maximum } S/N \text{ ratio for warpage} & \\ &= I_{t2} + P_{P3} + P_{PT3} + C_{T3} - 3 \times (\overline{Y_i}) \qquad (7a) \\ &= 6.957 + 6.980 + 6.916 + 6.854 - 3 \times (7.372) \\ &= 27.707 - 22.116 = 5.591 \text{ dBi}, \end{aligned}$$

$$\begin{aligned} \text{Maximum } S/N \text{ ratio for shrinkage} & \\ &= I_{t2} + P_{P2} + P_{PT1} + C_{T2} - 3 \times (\overline{Y_i}) \qquad (7b) \\ &= -14.23 - 14.41 - 15.11 - 14.32 - 5 \times (-14.78) \\ &= -58.07 + 44.34 = -13.73 \text{ dBi}, \end{aligned}$$

where $\overline{Y_i}$ is the average value of response and S/N ratio values for warpage and shrinkage. From these results, it can be realized that the minimum warpage and shrinkage are found to be 0.405 mm and 4.878%, which are smaller than 0.414 mm and 4.910% depended on the optimum levels of process parameters for plastic components of orthose part. In addition, warpage and shrinkage values of 0.414 and 4.910% are the smallest values among analysis results.

6. Verification test

A verification test is to control the accuracy of analysis results taken from various engineering applications. In

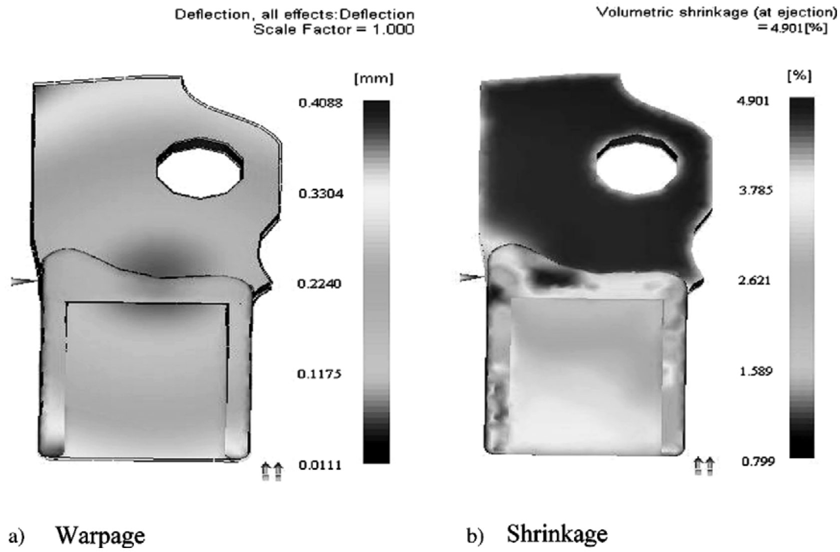

Fig. 6. Verification results from MoldFlow analysis.

other words, the verification test contributes to increase the efficiency of the applied process within the optimum levels of parameters. In this study, the verification test was carried out by means of the optimum levels of process parameters such as $\mathbf{I_{t1}P_{P1}P_{PT1}\ C_{T1}}$ and $\mathbf{I_{t2}P_{P3}P_{PT3}\ C_{T3}}$ for the minimum warpage and shrinkage resulted from optimization process. Based on the optimum levels of process parameters, warpage and shrinkage values were obtained and then, the results of those are shown in Fig. 6.

7. Results and discussion

From analysis results, the findings can be drawn as below:

- Based on ANOVA results, it is apparent that packing pressure (P_P) is most important parameter with a percent value of 58.03 on warpage and this was followed by packing pressure time (P_{PT}) of 23.03%, injection time (I_t) of 15.17%, and cooling time (C_T) of 3.68%, respectively.
- It is also seen that packing pressure time (P_{PT}) have most significant parameters with a percent value of 84.054 on shrinkage this was followed by packing pressure (P_P) of 7.83%, injection time (I_t) of 5.528%, and cooling time (C_T) of 2.588%, consecutively.
- After optimization process, the minimum warpage is calculated to be 0.405 mm, which is less than 0.414 mm in FE analyses of L_9 orthogonal array. It can be inferred that warpage is improved by about 2.17%.
- The minimum shrinkage is calculated to be 4.878%, which is less than 4.910% in FE analyses of L_9 orthogonal array. It can be concluded that shrinkage is improved by about 0.7%.
- Regarding verification test, it can be observed that the error between the predicted value of the minimum warpage and the analysed value of that is found as 1.26%. It can also show that the error between the predicted value of the minimum shrinkage and the analysed value of that is found as 0.2%.

8. Conclusion

This study was focused on the application of Taguchi optimization technique to find the optimum levels of process parameters used in injection of thin-shell plastic components for orthose part by improving the warpage problem with shrinkage variation. In doing this, the orthogonal arrays of L_{27} and L_9, the S/N ratio, ANOVA were utilized in integrated manner. To control the effectiveness of Taguchi optimization technique, a verification test was conducted during FE analyses of orthose part in MoldFlow. As a result, Taguchi optimization technique is very power tool to solve the warpage problem with shrinkage and it can be easily implemented for many industrial applications.

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