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Numerical Investigation of Warpage in Insert Injection-Molded Lightweight Hybrid Products

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In this study, a numerical investigation of warpage found within insert injection-molded frame parts was carried out based on the Taguchi method in conjunction with a response surface methodology. An integrated mold frame unit was recently developed by integrating a conventional mold frame, metal reflector, and bezel together, to be used in a back light unit system of a liquid crystal display. Such an integrated plastic-metal hybrid part could be successfully manufactured through the insert injection molding process. However, minimization or even elimination of warpage, one of the severe defects found in injection-molded products, is required for reliable mass production. Therefore, a numerical analysis was performed to reveal the effects of the relevant processing parameters, showing that packing pressure played the most significant role, originated from temperature difference between corners of the final product. Furthermore, a double optimization process combining the Taguchi method and the response surface methodology was employed to determine accurate and optimal processing conditions. The results clearly verified that the current combination technique can overcome the Taguchi method's limitation, resulted from a discrete optimization nature, and also effectively give more accurate optimum solutions without complicated algorithms and software.

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1. Introduction

Insert injection molding (IIM) is an advanced manufacturing technology that enables the mass production of complex-shaped plastic-based hybrid products. By placing metal inserts inside an injection mold cavity prior to filling it with molten polymers, a plastic-metal hybrid part can be precisely produced. In general, IIM has several advantages over other methods such as low cost, a short processing cycle, good mechanical properties, and excellent surface quality. To this effect, various plastic-metal hybrid parts, such as over-molded bearings, medical brace components, IC chip carriers, and mechanical threaded inserts, have been manufactured using the IIM process.[1-3]

Recently, we employed the IIM process to develop a novel integrated mold frame unit for application within a back light unit (BLU) system of a liquid crystal display (LCD). Typical components such as a mold frame, a metal reflector and a bezel were integrated, thereby producing a thin, lightweight, plastic-metal hybrid part. Even though the designed hybrid part was successfully manufactured using the IIM process, optimization of the relevant processing parameters was required to reduce distortion and warpage to improve dimensional quality.

Warpage is considered to be a severe defect of conventional injection molding. To address this undesired effect, there have been various research efforts aimed at investigating the warpage phenomenon of molded plastic parts. The properties of the constituent materials, the geometry of the product, and the manufacturing processing conditions are considered to be the primary factors affecting warpage. Amongst these factors, most of the investigations focused on the relevant processing parameters and/or their optimization to minimize warpage. For instance, La et al.,[4] Ozcelik and Sonat,[5] Azaman et al.,[6] Wang et al.,[7] Zafosnik et al.,[8] Chen et al.,[9] and Zheng et al.[10] used the Taguchi method to minimize warpage of the molded products. Similarly, Kurtaran and Erzurumlu,[11] Park and Dang,[12] and Li et al.[13] utilized a response surface methodology (RSM) in order to optimize parameters affecting warpage. Chen et al.[14] employed a combined dual technique of RSM and a commercial nonlinear programming technique (Lingo®) to outperform the Taguchi optimization method. Nian et al.[15] utilized neutral axis theory to do the same. Chen and Kurniawan[16] used a combination of the Taguchi method, an effective genetic algorithm, a back-propagation neural network (BPNN) to determinate the optimal process condition. Furthermore, Xu and Yang[17] proposed an integrated approach to improve

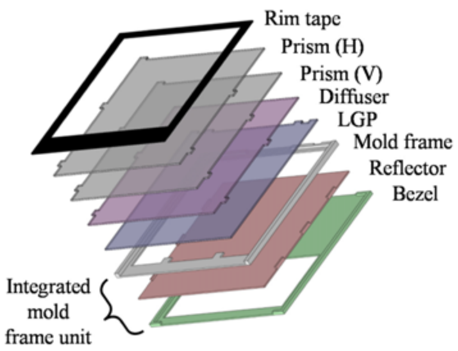

Fig. 1 Schematic illustration of the conventional BLU and the integrated mold frame unit developed in the present study

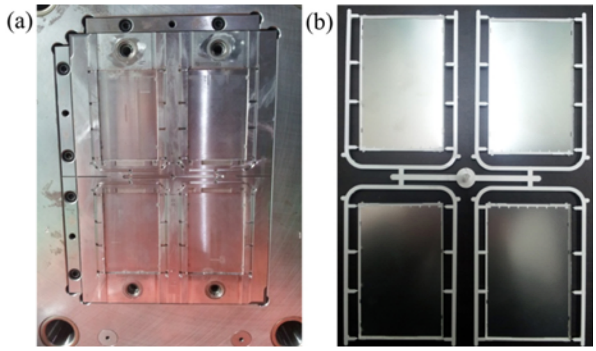

Fig. 2 Photographs of (a) the injection mold for the integrated mold frame unit and (b) the part produced with the mold

their optimization process, which was a combination of the Taguchi method, BPNN, grey correlation analysis, and a multi objective particle swarm optimization.

As described, the Taguchi method and RSM are commonly used techniques to determine the optimum values of the relevant processing parameters. However, applying a single one of these two techniques does not provide accurate optimization because of the discrete property of the Taguchi method as well as the intricate nature of the IIM process. Furthermore, incorporating a metal structure into the polymeric material complicates the optimization of the IIM process and requires consideration of additional parameters, namely temperature, as well as the properties of the inserted metal and the relevant processing parameters of the insert.

To this effect, a novel double optimization process that combines both the Taguchi method and RSM is proposed in this study. The Taguchi method was applied with consideration for the important processing parameters of the IIM process, resulting in intermediate optimum values. These obtained values were then used for subsequent RSM processing to determine the finely tuned optimum values. The double optimization process was applied to the IIM process to minimize warpage of the developed integrated mold frame unit. With this method, the effects of processing parameters on warpage of the plastic-metal hybrid part were investigated using the conditions that yielded minimal warpage.

2. Description of the Molded Hybrid Product

In this study, the warpage phenomenon of the integrated mold frame unit, which consisted of a plastic part and metal sheet, was investigated. Usually, the LCD-BLU was composed of optical films, a light guide panel, a mold frame, and a reflector as illustrated in Fig. 1. The mold frame, reflector, and bezel were combined to construct the integrated mold frame unit. The integrated part was efficiently manufactured by the IIM process using the injection mold shown in Fig. 2. Fig. 2(a) shows the mold core situated within the moving platen of the injection mold. It was designed to have four cavities with the metal reflectors installed before closing the mold. With the prepared injection mold, the plastic-metal hybrid part of the integrated mold frame unit could be fabricated. Fig. 2(b) shows four molded parts produced by the IIM process.

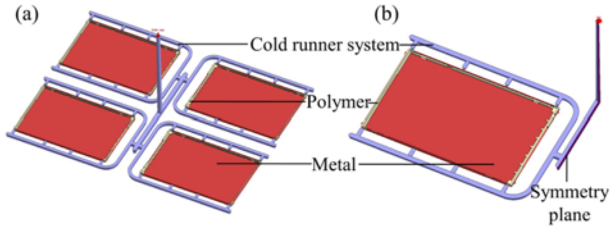

Fig. 3 Geometrical models of the integrated mold frame unit: (a) entire model with 4-cavities and (b) symmetry model for the numerical analysis

Table 1 Material properties of stainless steel and polycarbonate used in the numerical analysis

Stainless steel (JIS SUS410)		Polycarbonate (Starex LB1020, Cheil)	
Density (kg/m^3)	7.75×10^3	Density (kg/m^3)	1.27×10^3
Elastic modulus (GPa)	200	Elastic modulus (GPa)	2.28
Poisson's ratio	0.3	Shear modulus (GPa)	0.805
CLTE (1/K)	9.9×10^{-6}	Poisson's ratio	0.417
		CLTE (1/K)	7.3×10^{-5}

The materials used for the metal reflectors and plastic parts were stainless steel (JIS SUS410) of 0.2 mm thickness and polycarbonate (Starex LB1020, Cheil), respectively. Table 1 shows important properties of these two materials used in the numerical analysis.

For the numerical investigation, a geometrical model was constructed for the entire product, including the plastic parts, metal reflectors, and delivery system comprised of the sprue, runners, and gates. Fig. 3(a) shows the entire model construction based on the real injection mold. As the four parts were symmetrically designed and placed into the injection mold, a quarter of the model, shown in Fig. 3(b), was employed in the numerical analysis to reduce the required computational time. It should be noted that the symmetry boundary condition was assigned on the symmetry planes of the sprue and main runner.

In this study, the four-node tetrahedral elements were employed to discretize the computational domain. The thin cavity was constructed with 241,157 elements and 246,206 nodes while 754,423 elements and 758,358 nodes were used for the delivery system.

Table 2 Parameters for the generalized Maxwell model

Element	E_i (dyne/cm^2)	λ_i (sec)	Element	E_i (dyne/cm^2)	λ_i (sec)
1	1.16×10^9	0.002	5	2.89×10^6	10
2	8.68×10^8	0.05	6	8.68×10^5	150
3	1.16×10^8	0.35	7	3.61×10^5	3000
4	1.45×10^7	1.5	8	1.74×10^5	40000

3. Numerical Methods

3.1 Warpage simulation

In the present study, a full three-dimensional injection molding analysis software, Moldex3D®, was used to analyze the entire IIM process including the filling, packing, and cooling stages. During the polymer molding process, warpage of the molded part originates from an unequal volumetric shrinkage of material throughout the geometry of the plastic part as it cools from a molten state to a solid state. Variations in temperature and pressure induce changes in the specific volume and density of polymeric material, consequently resulting in warpage of the molded plastic part.

In order to precisely analyze the warpage phenomenon, the analysis software utilizes the Williams-Landel-Ferry (WLF) equation to generate a linear viscoelastic Maxwell model. The WLF equation was used as an empirical expression for the shift factor, and was usually employed to model the temperature dependency of polymeric materials.[18,19] The WLF equation is shown below:

$$\log a_T = -\frac{c_1(T - T_{ref})}{c_2 + T - T_{ref}} \tag{1}$$

where a_T is the time-temperature shift factor, T_{ref} is a reference temperature to which the master curves are generated by shifting the dynamic mechanical test data at other temperatures, and C_1 and C_2 are material coefficients determined by fitting the test data of the shift factor with the WLF equation. It should be noted that in this study 17.4, 51.6, and 143°C were used as C_1, C_2, and T_{ref}, respectively.

The generalized Maxwell model is created by adding multiple Maxwell elements in parallel. The generalized Maxwell model is a popular model used for the quantification of relaxation behavior of polymeric materials. Relaxation does not occur at a single time, but instead in a set of times because of the varying time distribution that result from the fact that molecular segments of shorter lengths contribute less than those of longer lengths. The generalized Maxwell model can be expressed as:

$$E(t) = E_\infty + \sum_{i=1}^{n} E_i \exp\left(-\frac{t}{\lambda_i}\right) \tag{2}$$

$$\lambda_i \equiv \frac{\eta_i}{E_i} \tag{3}$$

where λ_i, η_i, and E_i are the relaxation time, coefficient of viscosity, and elastic modulus of the i-th Maxwell element, respectively, n is the total number of Maxwell elements, and E_∞ is the final modulus or quasi-equilibrium value of the modulus of elasticity. Furthermore, according to Fan and Kazmer,[18] λ_i can be replaced by $a_t \cdot \theta_i$, where θ_i is the relaxation time of the i-th Maxwell element. Therefore, a linear relaxation modulus of $E(t, T)$ can be simply represented via Eqs. (1) and (2). It should be noted that E_∞ was set to a value of 7,030 Pa, and eight Maxwell elements were used. Table 2 shows the material parameters of the generalized Maxwell model, which were provided by Moldex3D Material Testing Lab. from the measurement using Anton Paar MCR 502 rheometer and ASTM D4065 procedure.

Table 3 Processing parameters and their detailed conditions investigated in the present study

Symbol	Parameter	Level		
		1	2	3
A	Filling time (s)	0.1	0.25	0.5
B	Packing time (s)	1	3	5
C	Packing pressure (MPa)	310	325	340
D	Melt temperature (°C)	290	300	310
E	Mold temperature (°C)	60	70	80
F	Cooling time (s)	10	15	20
G	Initial insert temperature (°C)	25	30	35

3.2 Optimization

Optimization in the IIM process can be considered as a determination of processing parameters that minimizes or maximizes a target property, while satisfying constraints. In the case of this study, the optimization problem is used to determine the relevant processing conditions resulting in minimal warpage of the molded hybrid part. A typical non-linear constrained optimization problem requires identifying a vector x that is a local minimum to a scalar function $f(x)$ subject to constraints within the allowable values of x; in other words:

$$\text{find} \min_{\vec{x}} f(\vec{x}) \text{such that} \begin{cases} c(\vec{x}) \le 0 \\ c_{eq}(\vec{x}) = 0 \\ A \cdot \vec{x} \le b \\ A_{eq} \cdot \vec{x} = b_{eq} \\ lb \le \vec{x} \le ub \end{cases} \tag{4}$$

In this study, a short MATLAB® script was written to determine the optimal values of the considered processing parameters. Since the calculated values vary depending on the optimization starting point, the whole range of parameters was divided into several sub-ranges with a designated starting point for each. Using this approach, a convergence into a local minimum could be avoided, and a global minimum within the range was instead obtained. The optimization module of Maple® was used to verify the optimal values obtained using MATLAB®.

4. Results and Discussion

4.1 Effect of molding parameters

4.1.1 Selection of molding parameter

There are many parameters capable of affecting the warpage of hybrid parts manufactured with an IIM process. Most of the processing parameters, such as filling time, packing time, packing pressure, melt temperature, mold temperature, cooling time, and initial insert temperature, were considered in the initial approach towards optimization. It should be noted that the effects of mold geometry including the sprue, runner, and gate were neglected in the present study. As a continuation of previous works, the present study focused

Table 4 Orthogonal array used in the present study: Detailed conditions for experimental sets and maximum warpage obtained by the numerical simulation (MSD represents mean standard deviation)

No.	Processing parameters							Warpage	MSD	S/N ratio
	A	B	C	D	E	F	G			
1	1	1	1	1	1	1	1	0.2086	0.043514	13.61371
2	1	2	2	2	2	2	2	0.2008	0.040321	13.94473
3	1	3	3	3	3	3	3	0.2332	0.054382	12.64543
4	2	1	1	2	2	3	3	**0.1854**	0.034373	14.63781
5	2	2	2	3	3	1	1	0.2147	0.046096	13.36336
6	2	3	3	1	1	2	2	0.2172	0.047176	13.26280
7	3	1	2	1	3	2	3	0.1910	0.036481	14.37933
8	3	2	3	2	1	3	1	0.2172	0.047176	13.26280
9	3	3	1	3	2	1	2	0.1907	0.036366	14.39299
10	1	1	3	3	2	2	1	0.2235	0.049952	13.01445
11	1	2	1	1	3	3	2	0.2011	0.040441	13.93176
12	1	3	2	2	1	1	3	0.2053	0.042148	13.75222
13	2	1	2	3	1	3	2	0.2109	0.044479	13.51847
14	2	2	3	1	2	1	3	0.2160	0.046656	13.31092
15	2	3	1	2	3	2	1	0.1916	0.036711	14.35209
16	3	1	3	2	3	1	2	0.2094	0.043848	13.58047
17	3	2	1	3	1	2	3	0.1918	0.036787	14.34303
18	3	3	2	1	2	3	1	0.1990	0.039601	14.02294
Sum								3.7074	0.766509	
Average								0.2060		13.74052

Table 5 S/N ratio results for each processing parameter

Parameters	A	B	C	D	E	F	G	Total
Level 1	13.4837	13.7907	14.2119	13.7535	13.6255	13.6689	13.6048	
Level 2	13.7409	13.6927	13.8301	13.9216	13.8873	13.8827	13.7718	41.2215
Level 3	13.9969	13.7380	13.1794	13.5462	13.7087	13.6698	13.8447	
Difference	0.5132	0.0979	1.0324	0.3754	0.2618	0.2137	0.2399	2.7344
Contribution %	18.77	3.58	37.76	13.73	9.57	7.82	8.77	100

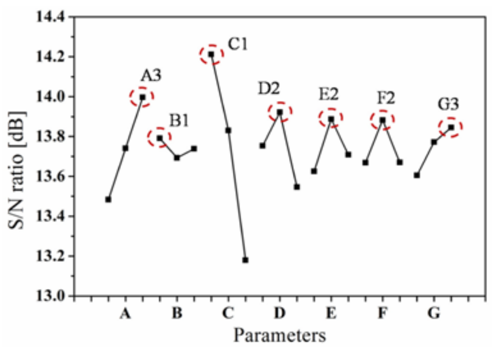

Fig. 4 Result of S/N ratio analysis showing the effect of processing parameters on the warpage

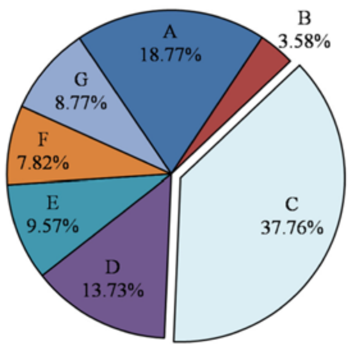

Fig. 5 Contribution chart of each processing parameter based on the S/N ratio analysis

on the optimization of the processing parameters for the mold design. Moreover, three levels of the processing condition for each parameter were established based on the recommended ranges. Table 3 lists the processing parameters and the three levels of conditions used in this study. With this approach, a DOE-based investigation and response surface model could be systematically constructed.

From the number of selected parameters and their respective levels, a subset of the L_{18} (21 × 37) orthogonal array was selected as shown in Table 4. A numerical simulation of the IIM process for the hybrid part was carried out using the parameter sets of the orthogonal array. The maximum warpage of the molded part, predicted by the numerical simulation, and the corresponding S/N ratio were also listed in Table 4. Since the warpage, the target characteristic of the study, should be minimized to achieve a high quality part, the "smaller-the-better" definition of the S/N ratio was used for calculating each S/N ratio.

4.1.2 Contribution of molding parameters

Table 5 shows the summarized S/N ratio results for each processing

Table 6 Result of ANOVA

Parameters	S	f	V	F	$F_{(0.05,2,3)}$	P%	Rank
A	0.000449	2	0.0002245	24.575295	9.55209	15.44	2
B	1.401×10^{-5}	2	7.007×10^{-6}	0.76706	9.55209	0.48	
C	0.0018578	2	0.0009289	101.69256	9.55209	63.89	1
D	0.0002551	2	0.0001276	13.963812	9.55209	8.77	3
E	0.0001124	2	5.619×10^{-5}	6.1510765	9.55209	3.86	
F	9.937×10^{-5}	2	4.969×10^{-5}	5.4393018	9.55209	3.42	
G	9.292×10^{-5}	2	4.646×10^{-5}	5.086425	9.55209	3.20	
Error	2.74×10^{-5}	3	9.134×10^{-6}				
Total	0.002908	17					

parameter. The results are also plotted in Fig. 4, which clearly depicts the effects of the processing parameters. For instance, the warpage of the molded hybrid part was found to increase with increasing filling time (parameter A), and decreasing packing pressure (parameter C) within the typical range of use. By evaluating the difference between maximum and minimum S/N ratio values, the contribution of each parameter was also obtained. Fig. 5 shows the contribution chart of the processing parameters. As shown, the packing pressure was found to be the most significant parameter influencing warpage.

To further investigate the contributions of the relevant processing parameters, an ANOVA approach was carried out as shown in Table 6. Consistent with the S/N ratio analysis, packing pressure, filling time, and melt temperature were found to be important parameters with respect to warpage reduction. Even though there was a qualitatively similar trend apparent in the S/N ratio and ANOVA analyses, there was a slight difference in the magnitudes of the processing parameter contributions. The ANOVA approach showed only three parameters, packing pressure, filling time, and melt temperature, as having bigger F values than $F_{(0.05,2,3)}$, thereby signifying that only these parameters were statistically meaningful.

To further analyze the effect of these three important processing parameters, the warpage of four corners of the hybrid product was investigated. According to their position with respect to the sprue, the four corners were classified into two groups – near corners and far corners. The magnitude of warpage of the near corners was found to be greater than that of the far corners for all cases considered in the numerical simulation. During the filling stage, the near corners of the plastic part were filled faster than those of the far corners, due to the shorter flow length. Therefore, they had lower melt temperatures and higher pressures as compared with the far corners. This could result in low fluidity during the subsequent packing stage, which is considered to be an important step of compensating for volumetric shrinkage by adding additional material. Therefore, after the transition from the filling stage to the packing stage, most of the additional flow induced by the packing pressure was applied to the far corners of the plastic part. This was verified by checking the flow rate variation through each gate and explains the reason for higher warpage found in the near corners of the plastic part.

While a high packing pressure usually tends to reduce warpage in a molded product, the simulation result in the present study showed increased warpage with increased packing pressure. Even though the high pressure was applied during the packing stage, it could not effectively influence the plastic part at the near corners. Because warpage is strongly related to the distribution of volumetric shrinkage, the applied packing pressure reduced the shrinkage of the plastic part at the far corners only, resulting in an increased difference in the shrinkage between the near and far corners. This provides an explanation for the increased warpage in the case where higher packing pressure was applied. Additionally, the filling time is inversely proportional to the flow rate during the filling stage. A low flow rate corresponds with a long filling time, thereby resulting in a smaller difference in the pressure distribution induced during the filling stage. Since a more uniform pressure distribution was achieved for parts produced with a low flow rate, the warpage of these parts was reduced.

4.1.3 Validation test

From the S/N ratio analysis, it was determined that the minimum warpage could be obtained under the processing conditions of A3-B1-C1-D2-E2-F2-G3 as indicated in Fig. 4. An additional simulation was carried out under these conditions as a validation test, showing that the maximum warpage in the hybrid part was 0.1818. This value was lower than warpage values of all the cases considered in the orthogonal array listed in Table 4.

Figs. 6(a) and (b) show the warpage distributions under the processing conditions of Case 4 in Table 4 and the improved conditions from the S/N ratio analysis, respectively. From the validation test, it was verified that the Taguchi method provides a better combination of processing conditions for minimizing warpage.

4.2 Optimization to minimize warpage

4.2.1 Generating response surface model

The Taguchi method is an efficient and powerful tool capable of providing the relative significance of each processing parameter and the improved combination of the relevant parameters for minimizing warpage.[20,21] However, the optimal values derived from the Taguchi method were limited to one of the three designated levels for each parameter. Therefore, RSM was employed to further reduce warpage of the molded hybrid part. In this study, the first-order response model was generated using the numerical results in Table 4. Using the least squares method, all the coefficients were determined, resulting in the following simple model. It should be noted that the coded or normalized parameters were used to determine the coefficients.

$$\begin{aligned} Warpage &= 0.205 - 6.122 \times 10^{-3} A + 8.058 \times 10^{-4} B \\ &+ 1.240 \times 10^{-2} C + 2.658 \times 10^{-3} D - 8.333 \times 10^{-4} E \\ &+ 1.750 \times 10^{-4} F - 2.781 \times 10^{-3} G \end{aligned} \tag{5}$$

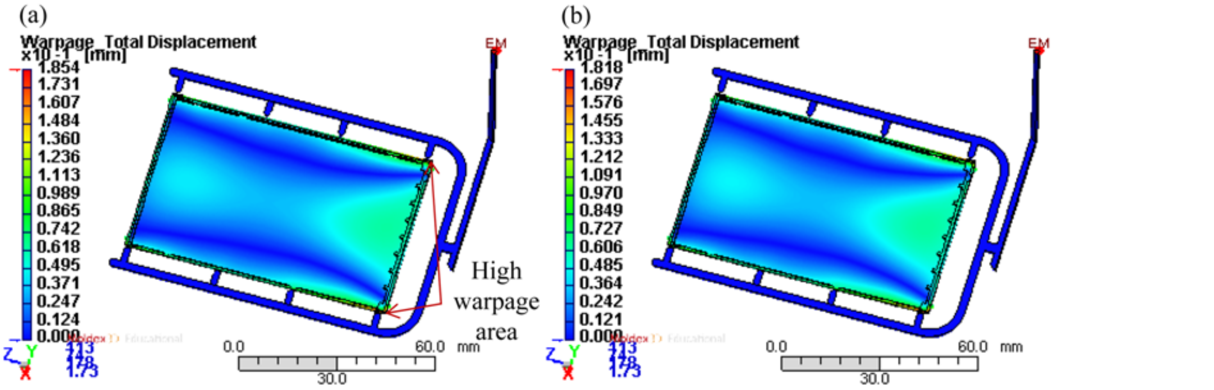

Fig. 6 Warpage distributions obtained by the numerical simulation: (a) under the processing conditions of case 4 and (b) under the new conditions from the S/N ratio analysis

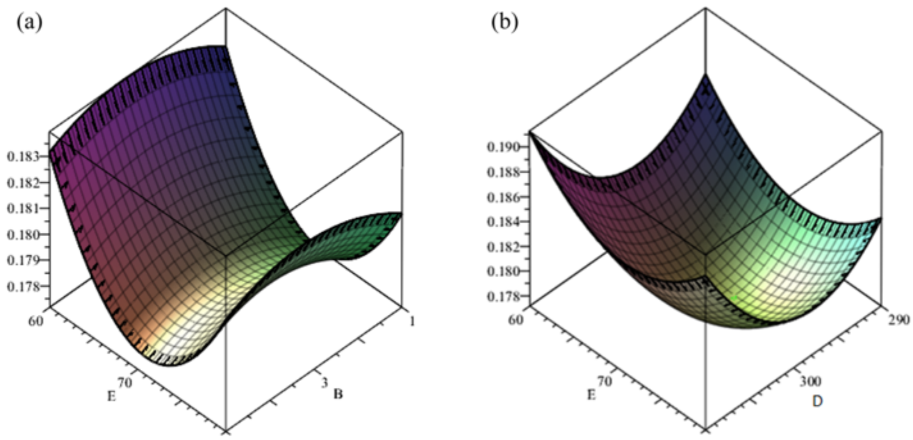

Fig. 7 Response surface of the warpage with respect to two parameters: (a) B (packing time) and E (mold temperature) and (b) D (melt temperature) and E (mold temperature)

From this model, parameter C (packing pressure) was found to have the most significant contribution since it had the largest coefficient. Parameter A (filling time) with the second largest coefficient had the second most significant contribution. This result was consistent with the previous S/N ratio analysis based on the Taguchi method. It should be noted that the first-order model showed parameter G (initial insert temperature) to be a more crucial than parameter D (melt temperature) with regard to minimizing warpage. It can be attributed to the relatively large error (R^2 of 0.862) in the regression, indicating that the model should be improved further.

To improve upon the RSM model, the second-order terms for all the parameters were included in the next step of analysis. Because there was no statistically significant correlation between parameters, the second-order terms accounting for the interaction of two parameters were not considered. The second-order response model in terms of the normalized parameters was as follows:

$$\begin{aligned} Warpage &= 0.192 - 5.777\times10^{-3}A + 3.439\times10^{-4}B \\ &+ 8.014\times10^{-3}C + 2.658\times10^{-3}D - 8.333\times10^{-4}E \\ &+ 1.750\times10^{-4}F - 2.319\times10^{-3}G + 1.903\times10^{-3}A^2 \\ &- 1.111\times10^{-3}B^2 - 5.707\times10^{-5}C^2 + 5.846\times10^{-3}D^2 \\ &+ 4.421\times10^{-3}E^2 + 4.296\times10^{-3}F^2 + 1.764\times10^{-3}G^2 \end{aligned} \tag{6}$$

In addition, by using the actual values of the parameters instead of normalized values, the second-order response model based on actual parameters could be obtained as described below:

$$\begin{aligned} Warpage &= 7.277 - 5.743\times10^{-2}A + 1.838\times10^{-3}B \\ &- 1.037\times10^{-2}C + 3.481\times10^{-2}D - 6.273\times10^{-3}E \\ &- 5.121\times10^{-3}F - 4.698\times10^{-3}G + 4.757\times10^{-2}A^2 \\ &- 2.777\times10^{-4}B^2 + 1.718\times10^{-5}C^2 + 5.846\times10^{-5}D^2 \\ &+ 4.421\times10^{-5}E^2 + 1.718\times10^{-4}F^2 + 7.058\times10^{-5}G^2 \end{aligned} \tag{7}$$

It should be noted that an R^2 value of 0.983 was calculated for these models, thereby demonstrating a nonlinear regression with acceptable error.

From these models, the response surface could be constructed for a visualization of the effects of the processing parameters. Fig. 7 shows representative examples of the response surface of this study. The response surface with consideration for parameters B (packing time) and E (mold temperature) is shown in Fig. 7(a). The response surface with consideration for parameters D (melt temperature) and E (mold temperature) is shown in Fig. 7(b). The minimum or lowest points represent the optimal values for the corresponding parameters.

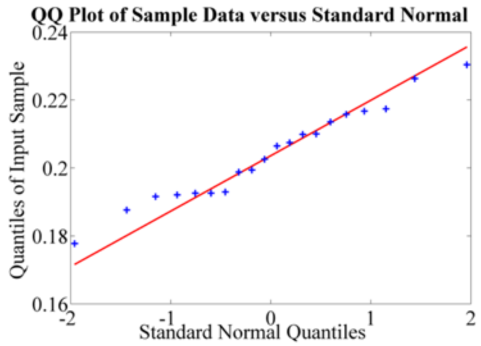

Fig. 8 Q-Q plot of the present response surface model

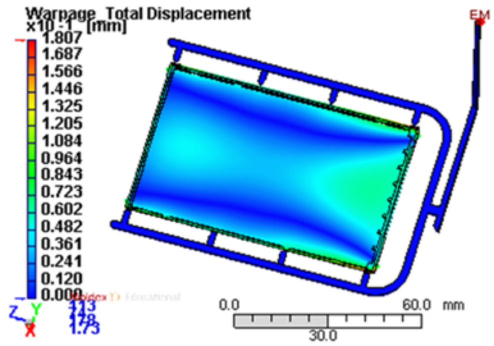

Fig. 10 Warpage distribution under the optimized processing conditions

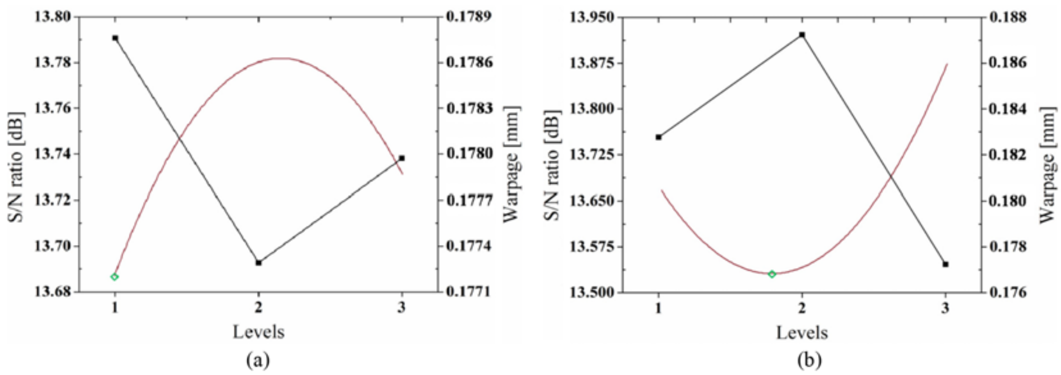

Fig. 9 S/N ratio plot and warpage estimated from the second-order response model: (a) effect of parameter B (packing time) and (b) effect of parameter D (melt temperature)

Table 7 Recommended processing conditions from the Taguchi method and RSM model

Symbol	Experimental parameters	Taguchi	RSM
A	Filling time (sec)	0.5	0.5
B	Packing time (sec)	1	1
C	Packing pressure (MPa)	310	310
D	Melt temperature (°C)	300	297.7264
E	Mold temperature (°C)	70	70.9424
F	Cooling time (sec)	15	14.8982
G	Initial insert temperature (°C)	35	33.2857
	Prediction values	N/A	0.1772
	Validation results	0.1818	0.1807

To verify the nonlinear regression and the generated surface response model, a Q-Q plot was used as shown in Fig. 8. This step was not emphasized by other authors, which could have resulted in wasted resources and inadequate RSM models found in their work. Fig. 8 shows that the model of this study was almost normally distributed.

To determine the optimal values of each processing parameter and minimize warpage, the obtained surface response model was employed. Fig. 9 shows the representative plots of S/N ratio and warpage predicted from the response model. As indicated in Fig. 9(a), both approaches predicted the same optimal values for parameter B (packing time). However, in the case of parameter D (melt temperature), the RSM approach provided a more accurate value than the S/N ratio analysis. As previously mentioned, this advantage of the RSM method over the S/N ratio analysis could result in a more finely tuned optimal value. Table 7 lists the optimal conditions for the processing parameters of both methods. A simple MATLAB® script was written and employed to determine the optimal values from the second-order response model. The optimization module of Maple® returned the same values as the MATLAB® script, thereby confirming the results. This shows that complicated algorithms and commercial software solutions can be avoided by utilizing tools, such as MATLAB®, to perform research with minimum resources. It is worth noting that the current step shows a simple method to globalize the local optimization built-in functions of MATLAB®.

4.2.2 Validation test

To validate the optimal processing conditions obtained using RSM, a validation simulation was carried out. As indicated in Table 7, the maximum warpage value of the molded hybrid product was calculated to be around 0.1807, which was smaller than any other warpage values calculated in this study. Moreover, the near corners of the plastic part showed larger warpage values than those of the far corners, as in other cases (shown in Fig. 10). This validation test shows that the combination of the orthogonal array technique used in the Taguchi method and RSM, i.e., double optimization, efficiently provides improved optimal values by using a minimal number of trials, and without requiring additional algorithms, optimization methods, or software solutions.

It should be noted that when the seven parameters are taken into account to generate the second-order response model, central composite design (CCD) and Box-Behnken design, which are commonly employed DOE techniques, require 79 and 57 trials, respectively. In this manner, the optimal processing conditions to achieve minimal warpage in the hybrid product can be efficiently obtained without additional screening of parameters. Hence, compared with other approaches, it was verified that the simple combination of the Taguchi method and RSM was enough to overcome the disadvantages of the Taguchi method as a discrete optimization method and to give better results in ranges without using other complicated algorithms, optimization methods or software solutions.

5. Concluding Remarks

In the present study, the double optimization technique was employed to investigate the effects of processing parameters on warpage of plastic-metal hybrid products, and also to determine the optimal conditions for minimal warpage. The optimization technique used in this study basically consisted of the orthogonal array technique of the Taguchi method used in conjunction with RSM. The newly developed integrated mold frame unit was selected as a representative model. In the numerical simulations of the IIM process of the hybrid product, seven processing parameters were considered. From the S/N ratio analysis and ANOVA based on the Taguchi method with an L_{18} (21 × 37) orthogonal array, the packing pressure was found to be the most significant parameter for minimization of warpage in the final product. RSM was applied to the results of the Taguchi analysis with a second-order nonlinear regression model to identify ideal processing conditions. Through this, the optimal parameter values were efficiently obtained and verified via the numerical simulation.

The simple and excellent performance of the double optimization used in this study demonstrates its utility in various manufacturing technologies and real manufacturing sites, where commercial optimization tools are not always available. The IIM process is one example where the current efficient method for mass manufacturing of plastic-metal hybrid products is directly applicable. The various processing parameters inherent to the IIM process show its complex nature. Therefore, the present method can be employed as an efficient tool to reliably manufacture plastic-metal hybrid products with high precision and minimal material consumption.

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