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Modeling and Analysis of Process Parameters for Evaluating Shrinkage Problems During Plastic Injection Molding of a DVD-ROM Cover

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Plastic injection molding plays a key role in the production of high-quality plastic parts. Shrinkage is one of the most significant problems of a plastic part in terms of quality in the plastic injection molding. This article focuses on the study of the modeling and analysis of the effects of process parameters on the shrinkage by evaluating the quality of the plastic part of a DVD-ROM cover made with Acrylonitrile Butadiene Styrene (ABS) polymer material. An effective regression model was developed to determine the mathematical relationship between the process parameters (mold temperature, melt temperature, injection pressure, injection time, and cooling time) and the volumetric shrinkage by utilizing the analysis data. Finite element (FE) analyses designed by Taguchi (L_{27}) orthogonal arrays were run in the Moldflow simulation program. Analysis of variance (ANOVA) was then performed to check the adequacy of the regression model and to determine the effect of the process parameters on the shrinkage. Experiments were conducted to control the accuracy of the regression model with the FE analyses obtained from Moldflow. The results show that the regression model agrees very well with the FE analyses and the experiments. From this, it can be concluded that this study succeeded in modeling the shrinkage problem in our application.

Keywords plastic injection molding, regression modeling and ANOVA, shrinkage

1. Introduction

Injection molding is one of the most efficient processes in mass production of manufactured plastic part with thin-shell features. The quality of the plastic part depends on the material characteristics, the mold design, and the process parameters, one of which is more important (Ref 1-3). Several studies found that the injection molding process parameters have crucial effects on the quality of the plastic parts (Ref 4-6). They investigated the problems of the injection molding part such as the shrinkage, warpage, weld line, sink marks, and residual stress generated by the process parameters. Their studies also show that the most important parameters affecting the quality of the plastic parts are packing pressure, melt temperature, and mold temperature. However, these studies did not examine in sufficient depth the effect of the other process parameters including injection time and cooling time. Further, Demirer et al. (Ref 7) have conducted an experimental research that evaluates the shrinkage and the warpage causing to the problems of the part quality. This research also explained that the shrinkage and the warpage increased with increasing the process temperature, decreased with increasing the injection pressure. In this research, although experimental conditions are enough to provide the valuable results, the major influential process parameters consisting of the injection time and the cooling time are not considered.

In the injection molding of the plastic parts as thin-shell features, many published papers have indicated that a statistical relationship can be built between the process parameters and the problems associated with the shrinkage and the warpage affecting the quality of the plastic parts (Ref 8-10). In the prior studies, a number of experiments were performed to measure the values of the shrinkage and the warpage under the process parameters. The mathematical models to determine the optimum process parameters were developed by exploiting the measured values. In the similar manner, the regression analysis is utilized to derive the relationship between the process parameters and the shrinkage based on the experimental through the injection molding of thin-shell plastic part (Ref 11, 12). Second-order generalized polynomial regression equations were created to derive this mathematical relationship on the shrinkage by the means of the process parameters. From these, it has also been found that the process plays statistically a key role in determining the quality of the plastic part. On the other hand, in the studies above, it is not employed any molding simulation tool (Moldflow analysis) for comparing the experimental results.

However, there are many articles investigating the simulation of the plastic injection molding which are influenced by the process parameters on the quality problems. One of the most significant of these articles is successfully applied by Chen et al. (Ref 13). This article deals with the application of computer-aided engineering integrating with statistical technique to reduce the warpage based on the

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plastic injection parameters. For this purpose, a number of Moldflow analyses dependent on the Taguchi orthogonal arrays, the regression equations, and analysis of variance (ANOVA) have been coupled to predict the warpage at various injection parameters. But, this article only summarizes the results of the warpage without those of the shrinkage during the plastic injection molding. Nevertheless, another article performed by Chen et al. (Ref 14) has employed for analysis and modeling of effective parameters on the shrinkage variation of injection molded part by exploiting a number of Moldflow analyses.

In contrast to the mentioned investigations, a different study was executed by Altan (Ref 15) to reduce the shrinkage in injection molding using Taguchi method, ANOVA, and Neural network. Twenty-seven injection molding experiments were performed to obtain the shrinkage values for two different polymer materials of Polypropylene (PP) and Polystyrene (PS). From this study, it can be seen that an integrated approach is presented to obtain minimum shrinkage corresponding to the best process conditions. As different from the literature above, some researchers only focused on the machining processes which are the Electric Discharge Machining (EDM) (Ref 16, 17). In summary, even though these researchers work the different fields, they have employed the similar methods as well as the plastic injection molding.

In this study, an effective regression model based on FE analyses obtained from Moldflow simulations was created to model the mathematical relationship between the plastic injection process parameters (the mold temperature, melt temperature, injection pressure, injection time, and cooling time) and the volumetric shrinkage using ABS polymer material. Most of the studies in the literature have not considered to all these process parameters. The ranges of the process parameters also differ from the studies in the literature. ANOVA analysis was performed to identify the most significant process parameters and to evaluate the adequacy of the regression model for the shrinkage of the plastic injection molding. Additionally, the experiments for four plastic injection moldings of the plastic part of a DVD-ROM cover were carried out to compare the shrinkage results of the simulated values with the measured values and to prove the accuracy of the regression model created.

2. Experimental Methodology

2.1 Taguchi Orthogonal Array Design of Experiments

The design of experiments utilizing the orthogonal arrays is, in most cases, efficient and easy to use when compared to the traditional experimental design methods. It is necessary to reduce and to control the number of experiments. Furthermore, a large number of experiments have to be performed when the number of process parameters increases. In this study, 27 FE analyses based on Taguchi (L_{27}) orthogonal arrays were run by utilizing plastic injection process parameters such as the mold temperature (T_{mold}), melt temperature (T_{melt}), injection pressure (P_{inj}), injection time (I_{time}), and cooling time (C_{time}) as shown in Table 1. The shrinkage parameter corresponds to the response value in developing the regression model. The shrinkage results obtained from FE analyses in Moldflow simulations are provided in Table 2.

Table 1 The levels of plastic injection moulding process parameters

No	Process parameters	Units	Levels
1	Mold temperature	T_{mold}, °C	40-60-80
2	Melt temperature	T_{melt}, °C	230-240-250
3	Injection pressure	P_{inj}, Mpa	80-100-120
4	Injection time	I_{time}, s	1-2-3
5	Cooling time	C_{time}, s	10-15-20

Table 2 Shrinkage results obtained from FE analyses

Analysis no	T_{mold}, °C	T_{melt}, °C	P_{inj}, MPa	I_{time}, s	C_{time}, s	Shrinkage, %
1	40	230	80	1	10	9.084
2	40	230	80	1	15	9.072
3	40	230	80	1	20	9.023
4	40	240	100	2	10	9.209
5	40	240	100	2	15	9.133
6	40	240	100	2	20	8.643
7	40	250	120	3	10	9.105
8	40	250	120	3	15	8.989
9	40	250	120	3	20	8.965
10	60	230	100	3	10	8.404
11	60	230	100	3	15	8.306
12	60	230	100	3	20	8.387
13	60	240	120	1	10	9.505
14	60	240	120	1	15	9.501
15	60	240	120	1	20	9.473
16	60	250	80	2	10	9.481
17	60	250	80	2	15	9.491
18	60	250	80	2	20	9.483
19	80	230	120	2	10	8.685
20	80	230	120	2	15	8.683
21	80	230	120	2	20	8.686
22	80	240	80	3	10	8.769
23	80	240	80	3	15	8.652
24	80	240	80	3	20	8.645
25	80	250	100	1	10	9.921
26	80	250	100	1	15	9.979
27	80	250	100	1	20	9.659

2.2 Mold Design and Manufacturing

When producing a plastic part, the molds must be designed and manufactured using various machines. In this study, the steps applied for manufacturing the plastic product of the DVD-ROM cover are described and shown in Fig. 1. In the plastic injection molding, the CAD model of the plastic product of the DVD-ROM cover was designed in the Pro/Engineer Wildfire CAD/CAM program. Also, the mold designed for the DVD-ROM cover consisted of two clamping plates, a core plates, and pins.

In fabricating the mold components, some machines such as CNC milling, EDM machining, drilling, and grinding were employed. The material utilized for the mold components was selected as DIN 1.2738 (IMPAX) steel. This material's hardness was measured to be 31 HRC with a Wolpert Instron Instrument and its chemical composition is presented in Table 3.

2.3 Finite Element (FE) Analysis and Molding Cycle

2.3.1 FE Pre-Processing of the DVD-ROM Cover. The 3D model of the DVD-ROM cover part was imported into the Moldflow Plastic Insight 5.0 (MPI 5.0) (Ref 18). The DVD-ROM

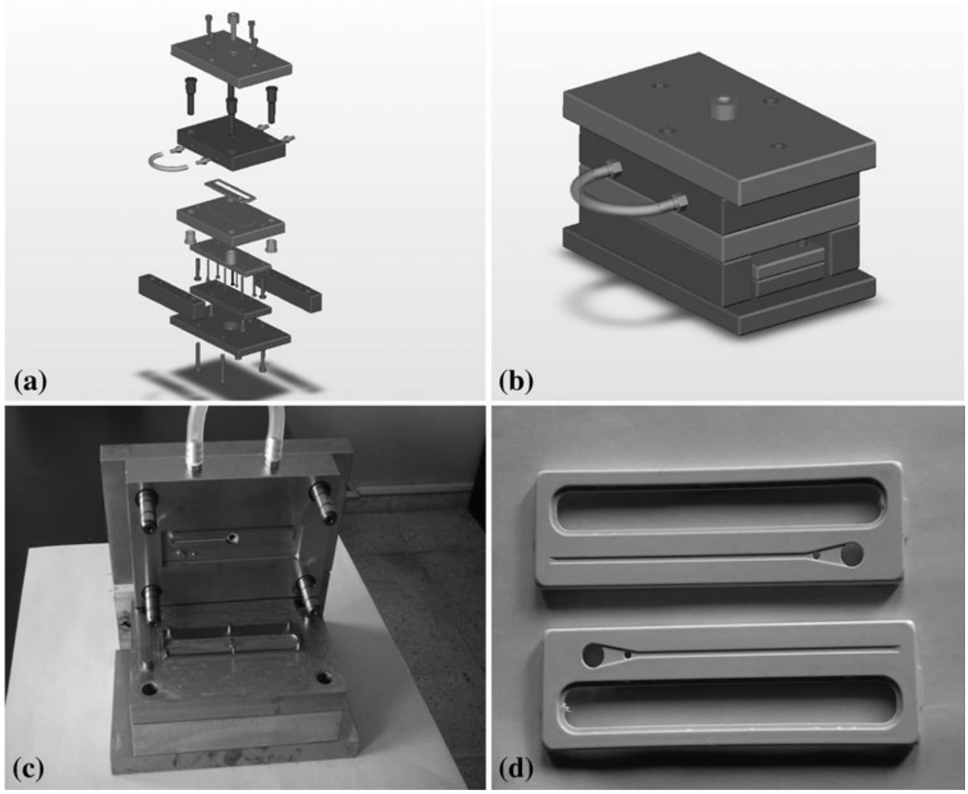

Fig. 1 The steps applied for producing the plastic product of the DVD-ROM cover

Table 3 DIN 1.2738 (IMPAX) material's chemical composition (%)

Carbon (C)	Silicium (Si)	Manganese (Mn)	Nickel (Ni)	Chrome (Cr)	Titanium (Ti)	Molybdenum (Mo)
0.396	0.292	1.418	1.109	1.855	0.043	0.214

Table 4 The material properties of ABS polymer

Commercial product name	LG Chemical (HI-121)
Melt density, g/cm^3	0.91459
Solid density, g/cm^3	1.0175
Material structure	Amorphous
Moldflow viscosity index	VI (240) 142
Thermal conductivity, W/m °C	0.1960
Specific heat, J/kg °C	2449
Modulus of elasticity, MPa	2240
Shear modulus, MPa	805
Poisson ratio	0.392

cover part has dimensions of 153, 45.17, and 7 mm. The polymer material (ABS) for the DVD-ROM cover part was composed of CMOLD generic estimates, and its material properties are listed in Table 4. The ABS polymer material was also dried for 4 h using a drier before the molding cycle. The FE model of the DVD-ROM part was created by discretizing the geometry into the smaller simple elements. The FE fusion mesh model, as shown in Fig. 2, consisted of 2726 nodes, 69 beam elements, and 5318 triangular elements.

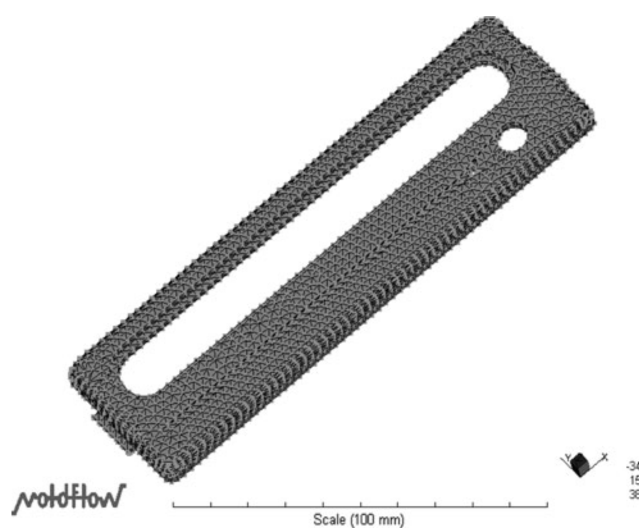

Fig. 2 The FE mesh model of the DVD-ROM cover product

2.3.2 Molding Cycle of the DVD-ROM Cover. The mold components were designed and manufactured to inject the plastic material of the DVD-ROM cover part, which is mounted on the front of a computer body to fix a DVD within a DVD-ROM. The plastic injection machine which is used in this study was a NETSTAL (600 H-110 60 tons 1.66 oz (25 mm)) made in Switzerland. This plastic injection machine has the technical specifications of a maximum clamp force of 543 tons, a maximum injection pressure of 243 MPa, a maximum injection rate of 491 cm^3/s, a screw diameter of 25 mm, and machine hydraulic response of 0.2 s.

3. Statistical Methodology

The factors (parameters) involved in an experiment can be either quantitative or qualitative. When the initial design and analysis are considered, both types of factors are treated identically. The experimenter tries to determine the differences between the levels of factors. The experimenter is usually interested in creating an interpolation equation for the response variable in the experiment. This equation is an empirical model of the process that has been evaluated. In general, the procedure used for fitting empirical models is called regression analysis (Ref 19).

3.1 Regression Modeling Approach

The aim of multiple regression modeling is to determine the quantitative relations between independent variables $(x_1, x_2, \ldots, x_k)$ and dependent variable (y). The relationship between these variables is characterized by a mathematical model which is called a regression model. The regression model is fit to set of sample data (Ref 19). Commonly used the mathematical models are represented as follows:

$$y = f(x_1, x_2, \ldots, x_k) \qquad \text{(Eq 1)}$$

A linear regression equation can be written as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \qquad \text{(Eq 2)}$$

This equation is a multiple linear regression model with two factors. The linear term is used because the, β_0, β_1, β_2, unknown parameters in Eq 2 and, ε, experimental error are a linear function. In general, the response (y) is associated with k regressor variables. In this case, the multiple linear regression models can be written as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \qquad \text{(Eq 3)}$$

These models are more complex than Eq 3 can be analyzed by the multiple linear regressions modeling approach. The first-order and the second-order models can be written as follows:

$$\begin{aligned} y &= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 \cdots + \varepsilon \\ x_3 &= x_1 x_2, \ \beta_3 = \beta_{12} \end{aligned} \qquad \text{(Eq 4)}$$

$$Y_1 = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_3 x_3 + \varepsilon \qquad \text{(Eq 5)}$$

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon \qquad \text{(Eq 6)}$$

$$\begin{aligned} & x_3 = x_{12}, x_4 = x_{22}, x_5 = x_1 x_2, \quad \beta_3 = \beta_{11}, \beta_4 = \beta_{11}, \beta_5 = \beta_{12} \\ & Y_2 = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \varepsilon \end{aligned} \qquad \text{(Eq 7)}$$

The method of the least squares is typically used to estimate the regression coefficients (β_0, β_1, β_2) in the multiple linear regression models. Y_1 is the response of the first-order model and Y_2 is the second-order model, respectively. The method of the least squares can be defined by the following equations:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_k x_{ik} + \varepsilon_i \qquad \text{(Eq 8)}$$

The least square method selects the β coefficients for minimizing the sum of the squared of the errors, ε_i. The final least square function can be written as follows:

$$L = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} \left(y_i - \beta_0 - \sum_{j=1}^{k} \beta_j x_{ij} \right)^2 \qquad \text{(Eq 9)}$$

3.2 Analysis of Variance

The objective of the analysis of variance (ANOVA) is to evaluate the effects of the process parameters on the response and to measure the adequacy of the statistics obtained from the multiple regression equations using the experimental data. In other words, ANOVA checks whether the effect of process parameters (factors) on the desired response is important or not. In addition, the ANOVA method is associated with the regression modeling approach. Therefore, it is essential to perform the general regression significance test by integrating the ANOVA method and the regression modeling approach. This situation can be expressed more clearly by the following equations:

$$SS_E = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad \text{(Eq 10)}$$

$$SS_T = \sum_{i=1}^{n} (y_i - \bar{\hat{y}}_i)^2 \qquad \text{(Eq 11)}$$

$$F = \frac{(SS_T - SS_E)/k}{SS_E/(n-k-1)} \qquad \text{(Eq 12)}$$

$$R^2 = 1 - \frac{SS_E}{SS_T} \qquad \text{(Eq 13)}$$

$$MSE = \frac{SS_E}{(n-k-1)} \qquad \text{(Eq 14)}$$

$$RMSE = \sqrt{\frac{SS_E}{(n-k-1)}} \qquad \text{(Eq 15)}$$

$$APE\ (\%) = \left\{ \left[\sum_{i=1}^{n} \left(\left| y_i - \hat{y}_i)^2 \right| / \hat{y}_i \right) \right] \Big/ p \right\} * 100 \qquad \text{(Eq 16)}$$

where n is the number of experiments y_i is the observed (measured) response, $\hat{y}_i$ is the fitted (desired) response, and $\bar{\hat{y}}_i$ is the mean value of y_i. Also, SS_E is the error sum of squares, SS_T is the total sum of squares, F is the test tool to control whether the regression model is statistically appropriate or not, R^2 (R-sq) is the correlation coefficient, R^2 (adj) is the adjusted statistic, MSE is the mean square error, RMSE is the root mean square error, and APE (%) is the average absolute percentage error.

4. Results and Discussion

The results obtained from the statistical and Moldflow analyses in this study have been investigated in two categories:

the first is the statistical results consisting of multiple regression and ANOVA analysis, and the second is the simulation results involving Moldflow analysis during the plastic injection molding process.

4.1 Statistical Results

A multiple regression analysis using Minitab (Ref 20) have performed to determine the mathematical relationship between the process parameters and the shrinkage obtained from the values of the FE analyses based on the plastic injection molding. For this purpose, the first-order and the second-order regression models have developed to find the values of the shrinkage when compared to the values from the FE analyses taken from Moldflow. After that, the ANOVA analyses have conducted to check the adequacy of the developed regression models and to evaluate the effects of the process parameters on the shrinkage.

The first-order regression model in terms of coded values of process parameters is given below:

$$\text{Shrinkage} = 1.01 + 0.00127T_{\text{mold}} + 0.0375T_{\text{melt}} - 0.0003P_{\text{inj}} - 0.389I_{\text{time}} - 0.0133C_{\text{time}} \quad \text{(Eq 17)}$$

Table 5 presents the results of the first-order regression model for the shrinkage. In Table 5, R^2, which is expressed in Eq 13, is the correlation coefficient and is called R-sq. When R^2 approaches the value of 1, the multiple regression models match very well with the experimental results. R^2 is calculated to be 0.959 (95.9%) by utilizing the first-order regression model given in Eq 17. The T value of the process parameters can be utilized to control whether the predictor significantly estimates the shrinkage. The P value indicates the significance of process parameters on the shrinkage. If the P values are less than 0.05 (i.e., $\alpha = 0.05$ or 95% confidence), the process parameters in the regression model are significant. As can be clearly seen in Table 5, T_{melt}, I_{time}, and C_{time} are statistically the most significant process parameters for the shrinkage. The other process parameters (T_{mold} and P_{inj}) are not significant because their P value is bigger than 0.05. Table 6 reveals the results of the ANOVA analysis showing that the process parameters on the shrinkage are statistically significant. The F value of 98.72 in Table 6 implies that the first-order regression model is significant. The bold value in Table 5 and 7 shows whether the process parameters are important or not.

The second-order regression model, in terms of coded values of process parameters, can be found as below:

$$\text{Shrinkage} = 1.14 + 0.0375\,T_{\text{melt}} - 0.489\,I_{\text{time}} - 0.0133\,C_{\text{time}} + 0.0251\,I_{time}^2 \quad \text{(Eq 18)}$$

Table 7 demonstrates the results of the second-order regression model for the shrinkage. In Table 7, R^2 is calculated to be 0.958 (95.8%) using the second-order regression model, as given in Eq 18. In Table 7, T_{melt}, I_{time}, C_{time}, and I^2_{time} are statistically the most significant process parameters for the shrinkage. The other process parameters (P_{inj} and T_{mold}) and their interactions are not significant because their P value is bigger than 0.05. Table 8 illustrates the results of the ANOVA analysis verifying that the process parameters for the shrinkage are statistically significant. The F value of 124.45 in Table 8 indicates that the second-order regression model is significant.

In the comparison of the results in Table 5 and 7, it can be seen that R^2 (R-sq) values are almost the same, both for the first-order and the second-order regression models. However, five process parameters, T_{mold}, T_{melt}, P_{inj}, I_{time}, and C_{time}, are used to develop the first-order regression model, whereas three process parameters, including T_{melt}, I_{time}, and C_{time}, are employed to develop the second-order regression model. The comparison of the ANOVA results in Table 6 and 8 shows that the F value (124.45) of the second-order regression model is greater than the F value (98.72) of the first-order regression model. This result indicates that the second-order regression model is more significant than the first-order regression model in terms of the statistical approach.

Table 5 The results of the first-order regression model

Predictor	Coefficient	SE coefficient	T	P
Constant	1.0120	0.6120	1.65	0.113
T_{mold}	0.001267	0.001225	1.03	0.313
T_{melt}	0.037461	0.002451	15.29	**0.000**
P_{inj}	−0.00030	0.001225	−0.24	0.809
I_{time}	−0.38861	0.02451	−15.86	**0.000**
C_{time}	−0.013322	0.004902	−2.72	**0.013**
S = 0.1040		R-Sq(pred) = 93.90%	R-Sq(adj) = 94.9%	
PRESS = 0.339428		R-Sq = 95.9%		

Table 6 ANOVA results for the first-order regression model

Source	DF	SS_E	MSE	F	P
Regression	5	5.3364	1.0673	98.72	0.000
Residual error	21	0.2270	0.0108		
Total	26	5.5634			

Table 7 The results of the second-order regression model

Predictor	Coefficient	SE coefficient	T	P
Constant	1.1415	0.6086	1.88	0.074
T_{melt}	0.037461	0.002438	15.36	**0.000**
I_{time}	−0.4888	0.1707	−2.86	**0.000**
C_{time}	−0.01332	0.004877	−2.73	**0.012**
I^2_{time}	0.02506	0.04224	0.59	0.559
S = 0.1035		R-Sq(pred) = 93.90%	R-Sq(adj) = 94.9%	
PRESS = 0.339428		R-Sq = 95.9%		

Table 8 ANOVA results for the second-order regression model

Source	DF	SS_E	MSE	F	P
Regression	4	5.3280	1.3320	124.45	0.000
Residual error	22	0.2355	0.0107		
Total	26	5.5634			

The first-order regression model is developed to obtain the values obtained from the FE analyses when compared to the simulated values. By utilizing the first-order regression model for the shrinkage, the maximum error (ME) and the average absolute percentage error (APE %) are found to be 3.895 and 0.678%, respectively. Figure 3 displays the comparison of the values of FE analyses with the simulated values obtained from the first-order regression model for the shrinkage. It can be observed that the values of the FE analyses agree with the simulated values.

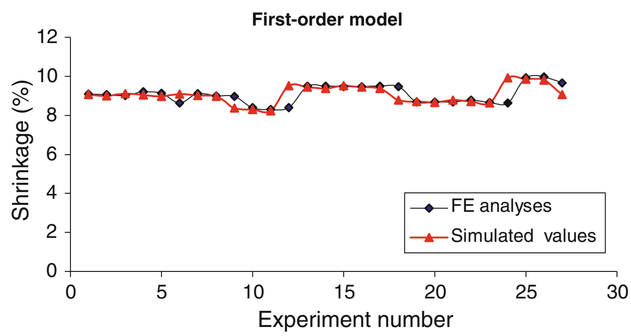

Fig. 3 Comparison of the values of FE analyses with the simulated values

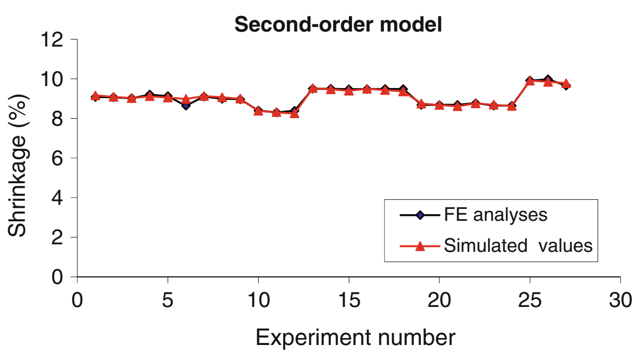

Fig. 4 Comparison of the values of FE analyses with the simulated values

The second-order regression model is developed to obtain the values obtained from FE analyses versus the simulated values. By employing the second-order regression model for the shrinkage, the ME and the APE (%) are found to be 3.994 and 0.705%, respectively. Figure 4 illustrates the comparison of the values of the FE analyses with the simulated values obtained from the second-order regression model for the shrinkage. It can also be observed that the values of FE analyses agree with the simulated values.

4.2 Simulation (Mold Flow) Results

The simulation results obtained from FE analyses run in Moldflow during the plastic injection molding of the plastic part of the DVD-ROM cover consisted of the variation of the volumetric shrinkage values under different process parameters and the other graphs (Fig. 6, 7) that relate to machine setups.

From the results of Table 2, it can be postulated that the shrinkage is highly influenced by the plastic injection parameters such as C_{time} and I_{time} when compared with the other parameters of T_{mold}, T_{melt}, and P_{inj}. The values of the shrinkage generally decrease as the C_{time} parameter increases at the injection times of 1, 2, 3 s. Further, the values of the shrinkage tend to decrease to the mold temperature from 40 to 60 °C at the first value of the injection time (1 s). After that point, they follow an irregular pattern.

Figure 5 displays the variation of the volumetric shrinkage with time in the Moldflow analyses. The simulation results of the volumetric shrinkage shown in Fig. 5 are selected from 27

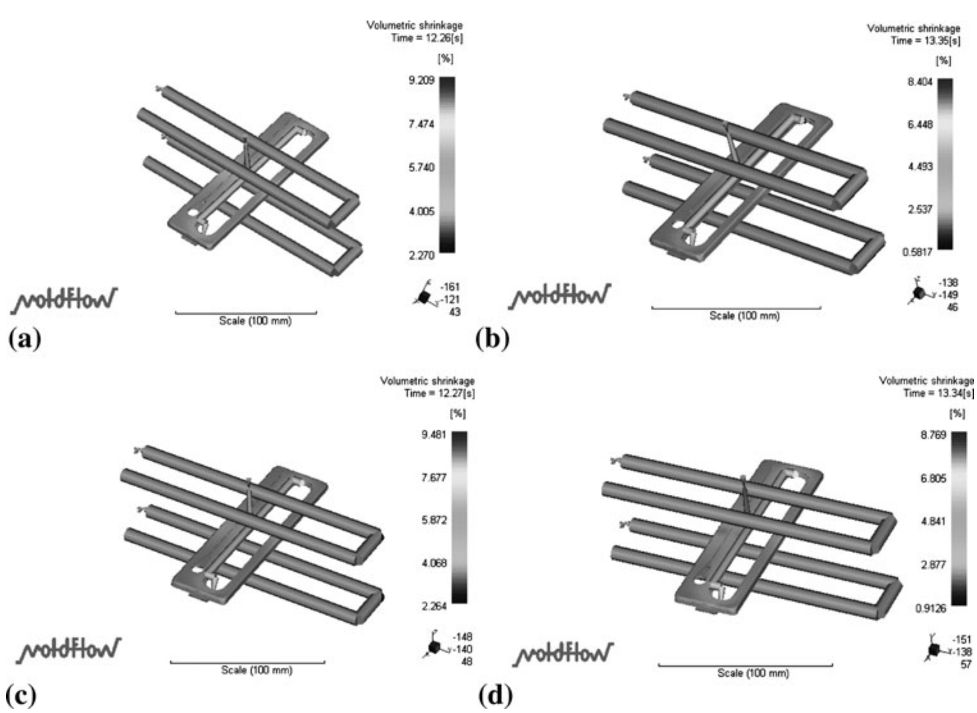

Fig. 5 The results of volumetric shrinkage with time for FE analyses of 4, 10, 16, and 22

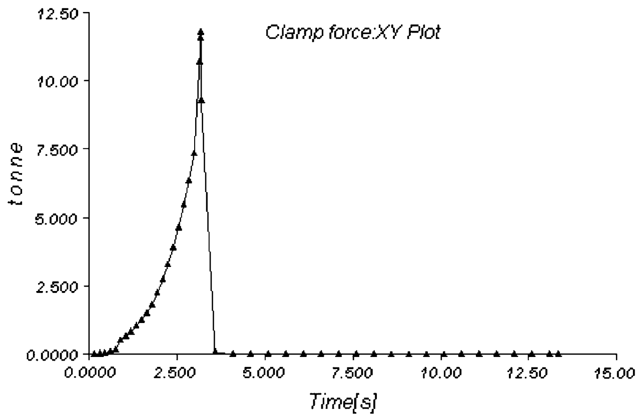

Fig. 6 The change of the clamp force with the time

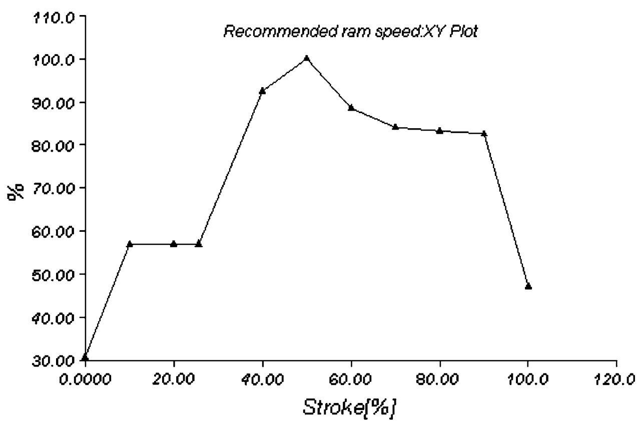

Fig. 7 The change of the recommended ram speed with the stroke

FE analyses equally. From the results shown in Fig. 5, it can be seen that the values of the volumetric shrinkage versus time exhibit an unstable trend for FE analyses of 4, 10, 16, and 22. Furthermore, these analyses demonstrate a general variation for all of the 27 FE analyses.

Figure 6 demonstrates the change of the clamp force in the plastic injection machine versus time for the plastic injection of the DVD-ROM cover. It can also be inferred that the clamp force increases regularly as the time increases to 3 s and after 3 s, it remains constant. Figure 7 indicates the change of the recommended ram speed with the stroke, and it can be emphasized that the recommended ram speed increases regularly as the stroke increases and then decreases continuously.

5. The Measurement of Experiments

The experiments for four plastic injection moldings of the plastic part of the DVD-ROM cover and their measurements, as shown in Fig. 8, were carried out to control the simulated values obtained from the developed regression model with FE analyses obtained from Moldflow. The four injection moldings were taken from ten plastic molding experiments (4 parts per 10 experiments). Five measurements were performed for a total of 40 experiments and each measurement was repeated at least three times. The formulation written in Eq 19 was utilized to control the simulated values with the FE analyses.

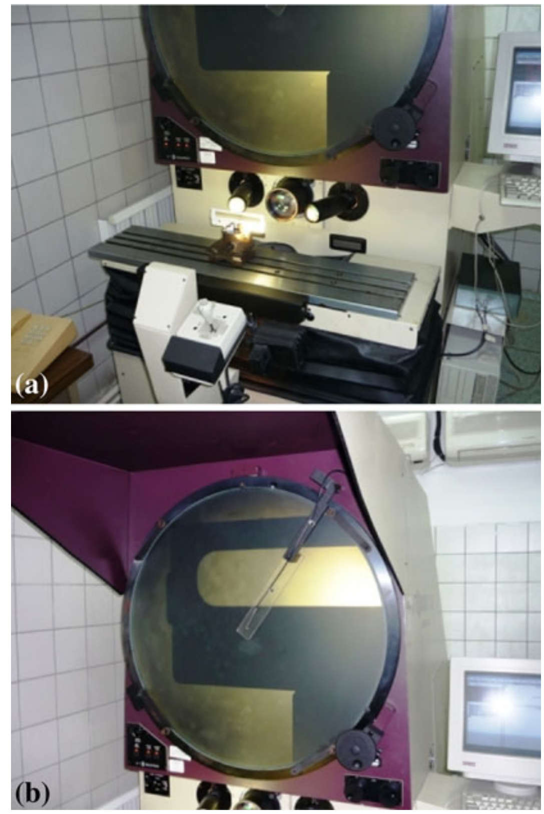

Fig. 8 The measurement of experiments

Here, L_{cavity} is the length of the mold cavity; L_{product} is the target length of the molded plastic part of the DVD-ROM cover. The values of L_{product} for the DVD-ROM cover were accurately measured by a profile control instrument (T-S INDUSTRIES Inc, St. James, MN).

$$\text{Shrinkage}\ (\%) = \left[\left(\frac{L_{\text{cavity}} - L_{\text{product}}}{L_{\text{cavity}}}\right) * 100\right] \qquad \text{(Eq 19)}$$

Table 9 shows the results of the measured values, the simulated values, and FE analyses. In Table 9, it can be seen that the measured values match very well with the simulated values and FE analyses. The APE was found to be 2.887% for the regression model (the simulated values) and 0.972% for the FE analyses.

6. Conclusion

In this study, an effective regression model was developed to determine the mathematical relationship between the plastic injection molding parameters and the volumetric shrinkage of the DVD-ROM cover. The orthogonal array of Taguchi (L_{27}) designed by the process parameters of the mold temperature, melt temperature, injection pressure, injection time, and cooling time was created to run 27 FE analyses in Moldflow simulation program. ANOVA analysis was performed to identify the most significant process parameters and to check the adequacy of the regression model developed on the shrinkage. Based on the first-order and the second-order models for the shrinkage, the maximum error (ME) was found to be 3.895 and 3.994 %, respectively. Finally, the experiments consisting of four plastic

Table 9 The results of the experiments

Experiment no	Measured values	Simulated values	FE analyses	The errors (APE %)	
				Regression model	FE analyses
4	9.252	9.046	9.209	2.887	0.972
10	8.636	8.309	8.404		
16	9.671	9.452	9.481		
22	8.977	8.714	8.769		

injection moldings of the DVD-ROM cover were conducted to confirm the shrinkage values calculated from the regression model developed with FE analyses obtained from Moldflow. As a result, it is seen that the this study is sufficient to model the shrinkage under the process parameters and efficient to apply the other problems such as the warpage, weld line, sink marks, and residual stress encountered in the plastic industry.

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