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A study of the effects of process parameters for injection molding on surface quality of optical lenses

Kuo-Ming Tsai, Chung-Yu Hsieh, Wei-Chun Lo*

Department of Mechanical Engineering, National Chin-Yi University of Technology, Taiping City, Taichung County, Taiwan, ROC

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ABSTRACT

The purpose of this study is to determine the effects of process parameters on optical quality of lenses during injection molding. The quality characteristics chosen are light transmission, surface waviness and surface finish. The Taguchi method is used to perform screening experiments to identify the important significant process parameters affecting quality of lenses. Through empirical and theoretical analysis, the most significant process parameters affecting surface waviness is the melt temperature, followed by mold temperature, injection pressure and packing pressure. On the other hand, injection molding process parameters are found to have little effect on light transmission and surface finish of lenses. Regression approach is then implemented based on surface waviness data from full factorial experiments to formulate the regression models. Three different regression methods are used, namely, linear, exponential and nonlinear regression. Verification experiments are executed to examine the accuracy of the regression model for predicting quality characteristics of lenses. The result showed the highest accuracy prediction of surface waviness was from a nonlinear regression model. An error of only 4.24% suggested the existence of a correlation among injection molding process parameters.

1. Introduction

The injection molding is one of the most efficient processes where mass production through automation is feasible and products with complex geometry are easily attained. The injection molding process cycle can be divided into three stages: filling, packing and cooling. Although the molding processes are quite simple, the rheological behaviors of polymers are complicated. Therefore quality characteristics of injected products are highly unpredictable. The desired combination of process parameters is generally acquired by an extended accumulation of experiences from the operators.

With the development of opto-information industry and optoelectronic technology, various precise optical elements and optoelectronic systems are produced. Optical lens is one of the key components in these fields, and has extensive applications such as digital camera, optical imaging, and multimedia cell-phone, etc. Earlier optical systems are generally composed of multiple spherical lenses; however, due to the increase demand of lighter, thinner, shorter, smaller and cheaper products, aspheric lens has become the favorite choice. During the injection processing, there is a strict correlation between process parameters and the quality of aspheric lenses. For instance, improper settings of process parameters will induce defects on the products, such as warpage, shrinkage, sink mark and residual stress. Since the optical performance of an optical lens is highly sensitive to surface contours of molds, these defects will severely affect

* *Corresponding author at*: Department of Mechanical Engineering, National Chin-Yi University of Technology, 35, LN 215, SEC 1, Chung Shan Road, Taiping City, Taichung County 411, Taiwan, ROC. Tel.: +886 4 23924505x7175; fax: +886 4 23930681.
E-mail address: tsai101@ncut.edu.tw (K.-M. Tsai).
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the product in the dimensional precision and optical performance (Hecht, 2002). Several investigators proposed different solutions to improve quality of molded product through theoretical and computational analysis, experimental studies and changes in mold designs. In theoretical analysis, governing equations for flow analysis by 1D model (Cao and Shen, 2005), 2D model (Seow and Lam, 1997; Cao and Shen, 2005; Kang et al., 2007), 2.5D mid-plane model (Huang and Tai, 2001; Bakharev et al., 2005), true 3D model (Choi and Im, 1999; Koo and Choi, 2005; Kim and Turng, 2006; Chang et al., 2007a; Chau and Juang, 2007) and hybrid models (Yu et al., 2004; Shen and Cao, 2006; Choi and Koo, 2007) are derived to predict and reduce defects by means of simulation through commercial CAE software or programs of their own. On the other hand, there are many articles investigating injection molding through experimental studies. Taguchi parameter design is usually employed to identify important processing conditions and obtain the combination of optimum processing conditions to improve the quality of products (Chen et al., 1997; Chang, 2001; Wu and Su, 2003; Kurtaran et al., 2005; Postawa and Koszkul, 2005; Ozcelik and Erzurumlu, 2006a,b; Okten et al., 2007; Tang et al., 2007). In these works, filling flow rate, filling time, injection velocity, melt temperature, mold temperature, packing pressure, packing period and cooling time are always the main processing parameters in the experiments. However, parameters regarding mold design are not commonly considered crucial for the process. Therefore, the relationships between the processing parameters and defects in various polymer materials are developed. High-quality molded parts are sensitively dependent on adaptive processing conditions settings. Moreover, several novel mold design techniques could clearly reduce defects on the product and produce a better temperature distribution within the mold. These works incorporate improved runner systems (Chien et al., 2005, 2007; O-Charoen et al., 2006; Rhee et al., 2006; Takarada et al., 2006), gate locations (Baesso and Lucchetta, 2007; Ryim and Yun, 2007) and the cooling system (Chiou et al., 2007). A second-order generalized polynomial regression model for shrinkage and weight of the molded parts based on experimental data was also conducted (Chang, 2001). The shrinkage and weight of the injection-molded product could be effectively predicted using the model. In the injection molding of plastic optical lenses, many published papers have indicated that the processing parameters have significant effects on the quality of the molded lenses (Lu and Khim, 2001; Pazos et al., 2003; Park and Joo, 2005; Young, 2005; Chang et al., 2007b; Chau and Lin, 2007; Wang and Lai, 2007), and that the birefringence induced by residual stress and quality of surface contour on the molded lenses is a very crucial problem for optical performance of lenses with large thickness variations. They always use simulations of CAE tool and experimental methods to reduce the defects of the optical lenses in their investigations. In summary, it is very complicated but essential to determine the processing conditions for injection molding in order to obtain products with highest quality. The objective of this work is to identify experimentally the main effects of the processing conditions on the surface contours of lenses and to obtain various regression models based on significant factors.

In order to obtain lenses with desired optical qualities, in addition to high precision molds, process parameters for injection molding is of crucial importance. Therefore a systematic study on process parameters of injection molding is required. In this paper, optical grade polymer, PMMA, is used to study the relationship between process parameters of injection molding and quality characteristics of optical lenses. The Taguchi method is first used to determine the effect of control factors on quality of lenses, and to identify the significant factors for injection molding. Full factorial experiments are then implemented based on these significant factors, and the data obtained are employed in regression analysis. Finally, confirmation experiments are carried out to verify the validity of regression model. The process model established helps grasp the effect of process parameters on quality characteristics of optical lenses.

2. Experimental procedures

2.1. *Experimental facilities*

The experimental facilities in this study can be divided into injection molding and measurement equipment. The injection molding equipment used is 220S 250-60 precision injection machine by ARBURG Germany, with an injection volume of 20 ml. The measurement equipment used is the Form Talysurf contour measurement system made by Taylor Hobson England, and the Cary 100 conc spectrometer made by Varian USA. The mold used for injection molding in this study is a 150 mm × 150 mm dual-plate style. In order to facilitate measurement, the two surfaces on lens are made flat and spherical, respectively, as shown in Fig. 1. The experimental material used in this study is PMMA-80N® made by the Asahi Kasei Chemical Corp. Japan. The polymer pellets are baked in an oven for 3 h prior to injection molding to remove moisture in the material. The mold is designed with two cavities, and samples are taken from the same side of the mold to minimize the difference in surface qualities on cavities.

2.2. *Taguchi experiments*

During the experiments, fractional factorial designs were used to study the coupling effects of all the factors on the final responses (Peace, 1993; Ross, 1996; Montgomery, 2001). This methodology provides a suitable tool for screening various factors with limited experimental results. Based upon the assumptions of the fractional factorial designs, certain high-order interactions are negligible; therefore, the major coupling effects and low-order interactions can be determined from the partial factorial experiments. The Taguchi method is usually

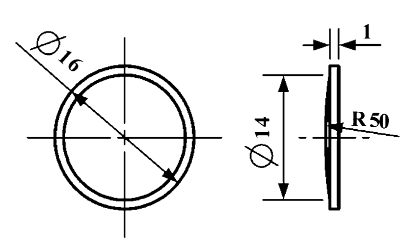

Fig. 1 – Dimensions of optical lenses.

Table 1 – The control factors and levels of the Taguchi experiments

Control factor	Level		
	1	2	3
(A) Melt temperature (°C)	230	220	
(B) Screw speed (m/min)	5	10	15
(C) Injection speed (mm/s)	50	70	90
(D) Injection pressure (bar)	900	1000	1100
(E) Packing pressure (bar)	1100	1200	1300
(F) Packing time (s)	7	10	13
(G) Mold temperature (°C)	60	70	80
(H) Cooling rate (s)	10	15	20

used to identify the significant factors for quality characteristics of the products.

The experiments are executed according to L18 ($2^1 \times 3^7$) orthogonal array, and the factor levels are listed in Table 1. In the L18 ($2^1 \times 3^7$) orthogonal array, column 1 is a two-level factor, and columns 2–8 are three-level factors. With the help of the array, the interactions between columns 1 and 2 can be investigated without having individual interactions with a specific column, i.e., however, the mutual interactions among three-level factors cannot be obtained from the array. As a result, the effects of interactions among the three-level columns are uniformly distributed. In this paper, eight control factors are chosen, namely melt temperature, screw speed, injection speed, injection pressure, packing pressure, packing time, mold temperature and cooling time.

2.3. *Quality characteristics*

The quality characteristics of optical lenses can be divided into geometric characteristics and optical characteristics. In this study, surface waviness and roughness of lenses are chosen as the geometric characteristics, and are measured in an aspheric contour measurement system. Optical lenses generally strive for lowest contour error and roughness. Therefore they are the smaller-the-better (STB) in terms of quality characteristics. According to the Taguchi experimental method (Peace, 1993), the S/N (signal-to-noise) ratio for STB, (η_{STB}), is defined as

$$\eta_{\text{STB}} = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \tag{1}$$

Light transmission is selected as the optical characteristics for lenses in this study, and is measured by a spectrometer. The light transmission as a quality characteristic is the larger-the-better (LTB) in nature, and the S/N ratio for LTB, (η_{LTB}), is defined as

$$\eta_{\text{LTB}} = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right] \tag{2}$$

The overall procedures of the Taguchi experiments are shown in Fig. 2.

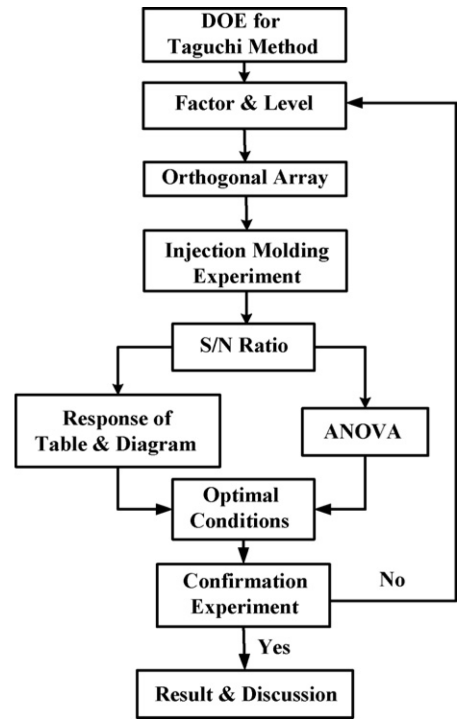

Fig. 2 – The procedures of the Taguchi experiments.

2.4. *Signal-to-noise ratio analysis*

2.4.1. *Surface waviness*

Table 2 shows the experimental results and S/N ratios (η value) of 18 different experimental conditions as the control factors of injection molding. The results revealed excellent repeatability of data on surface waviness of lenses for the same injection parameters. Different surface waviness is obtained for various working conditions, and the maximum variation of waviness is 0.5 μm. Fig. 3 shows the Taguchi response diagram for the surface waviness. The optimum combination of process parameters is $A_1B_3C_2D_3E_3F_3G_3H_1$, namely, a melt temperature of 230 °C, screw speed of 15 m/min, injection speed of 7 mm/s, injection pressure of 110 MPa, packing pressure of 130 MPa, packing time of 9 s, mold temperature of 80 °C and a cooling time of 10 s.

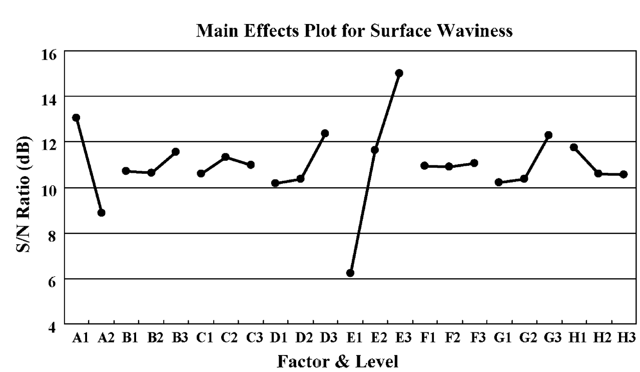

Fig. 3 – Response diagram for surface waviness in the Taguchi experiments.

Table 2 – The Taguchi L_{18} ($2^1 \times 3^7$) orthogonal array with experimental results

Exp. no.	Control factor								Waviness (μm)			Roughness (μm)			Transmission (%)			S/N ratio (dB)		
	A	B	C	D	E	F	G	H	1	2	3	1	2	3	1	2	3	Waviness (η_{STB})	Roughness (η_{STB})	Transmission (η_{LTB})
1	1	1	1	1	1	1	1	1	0.4382	0.4564	0.4377	0.0106	0.0109	0.0115	92.9900	92.9900	92.9900	7.05	39.17	39.37
2	1	1	2	2	2	2	2	2	0.2396	0.2396	0.2456	0.0100	0.0120	0.0116	91.6067	91.6067	91.6067	12.34	38.99	39.24
3	1	1	3	3	3	3	3	3	0.1064	0.1055	0.1098	0.0113	0.012	0.0112	90.6767	90.6767	90.6767	19.39	38.78	39.15
4	1	2	1	1	2	2	3	3	0.2420	0.2238	0.2359	0.0104	0.0098	0.0102	90.5733	90.5733	90.5733	12.61	39.88	39.14
5	1	2	2	2	3	3	1	1	0.1623	0.1405	0.1596	0.0120	0.0103	0.0106	91.9667	91.9667	91.9667	16.22	39.18	39.27
6	1	2	3	3	1	1	2	2	0.4132	0.3848	0.4084	0.0120	0.0130	0.0159	91.2000	91.2000	91.2000	7.91	37.24	39.20
7	1	3	1	2	1	3	2	3	0.4204	0.4304	0.4351	0.0105	0.0104	0.0137	92.2000	92.2000	92.2000	7.36	38.68	39.29
8	1	3	2	3	2	1	3	1	0.1094	0.1254	0.1223	0.0111	0.0111	0.0160	91.9633	91.9633	91.9633	18.47	37.76	39.27
9	1	3	3	1	3	2	1	2	0.1594	0.1585	0.1538	0.0116	0.0108	0.0113	92.7133	92.7133	92.7133	16.07	38.99	39.34
10	2	1	1	3	3	2	2	1	0.1908	0.2049	0.2249	0.0118	0.0125	0.0125	91.5500	91.5500	91.5500	13.67	38.22	39.23
11	2	1	2	1	1	3	3	2	0.6000	0.5989	0.6084	0.0143	0.0106	0.0098	91.3833	91.3833	91.3833	4.40	38.61	39.22
12	2	1	3	2	2	1	1	3	0.4321	0.4326	0.4236	0.0108	0.0103	0.0096	91.7200	91.7200	91.7200	7.34	39.79	39.25
13	2	2	1	2	3	1	3	2	0.2244	0.2141	0.2298	0.0114	0.0104	0.0099	91.7000	91.7000	91.7000	13.04	39.51	39.25
14	2	2	2	3	1	2	1	3	0.5896	0.5640	0.5735	0.0109	0.0117	0.0109	91.6733	91.6733	91.6733	4.79	39.04	39.24
15	2	2	3	1	2	3	2	1	0.3474	0.3504	0.3403	0.0102	0.0103	0.0114	91.6133	91.6133	91.6133	9.22	39.46	39.24
16	2	3	1	3	2	3	1	2	0.3214	0.3187	0.3261	0.0118	0.0124	0.0149	91.0500	91.0500	91.0500	9.84	37.65	39.18
17	2	3	2	1	3	1	2	3	0.2526	0.2676	0.2565	0.0125	0.0156	0.0125	91.5733	91.5733	91.5733	11.73	37.32	39.24
18	2	3	3	2	1	2	3	1	0.5108	0.5083	0.5106	0.0112	0.0109	0.0130	90.8533	90.8533	90.8533	5.85	38.61	39.17
Average																		10.96	38.72	39.23

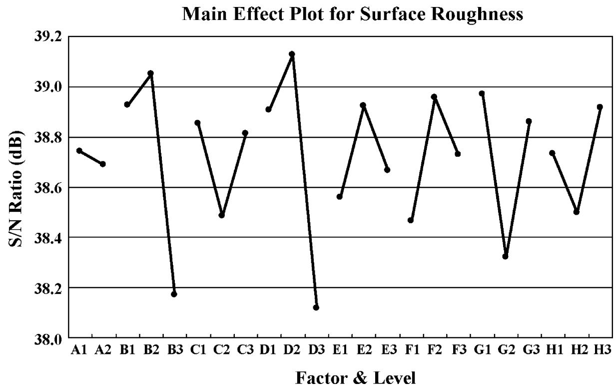

Fig. 4 – Response diagram for surface roughness in the Taguchi experiments.

Table 2 shows the results of the Taguchi experiment on surface waviness of lenses. The results for analysis of variance, ANOVA, of S/N ratio on quality characteristics are shown in Table 3. The result revealed that the significant injection parameters affecting surface waviness of lenses are packing pressure and melt temperature, at confidence interval of 95%. Analysis of variance is effective for identifying significant factors of a process, but not for the determination of optimum level value. The optimum level value can be determined from the response diagram shown in Fig. 3.

2.4.2. *Roughness*

Table 2 shows the results of the Taguchi experiment on roughness of lenses. The data indicate that the control factors only have a minor effect on roughness of lenses. A difference of 4–5 nm was observed among the various selected conditions. Fig. 4 shows the response diagram for roughness in the Taguchi experiments. The optimum combination of process parameters is $A_1B_2C_1D_2E_2F_2G_1H_3$, namely, a melt temperature of 230 °C, screw speed of 10 m/min, injection speed of 70 mm/s, injection pressure of 100 MPa, packing pressure of 120 MPa, packing time of 4 s, mold temperature of 60 °C and a cooling time of 20 s. However, the result of F and P_r values from analysis of variances revealed that the control factors have only marginal effect on roughness, at confidence interval of 95%. Since the surface morphology of lenses is a replication of the mold. A mold with a rougher insert produces a rougher surface finish of a lens, however, the process parameters have only limited effects.

2.4.3. *Light transmission*

A high light transmission of 91–93% is observed for optical grade PMMA lenses, as shown in Table 2. It is apparent from the response diagram in Fig. 5 that the variation of S/N ratios between factor levels is small. Table 3 shows the result of the analysis of variances for experimental data where process parameters have only marginal effect on light transmission of lenses. This implies the absence of direct correlation between process parameters and light transmission of lenses.

Table 3 – Analysis of variance data

	d.f.	SS			VS			F			Pr[a]		
		Waviness	Roughness	Transmission	Waviness	Roughness	Transmission	Waviness	Roughness	Transmission	Waviness	Roughness	Transmission
A[b]	1	78.292	0.0118	0.0035	78.292	0.0118	0.0035	74.72	0.02	0.45	0.013	0.895	0.573
B	2	3.17	2.7419	0.0021	1.585	1.3710	0.0011	1.51	2.58	0.14	0.398	0.279	0.881
C	2	1.599	0.4901	0.0016	0.799	0.2451	0.0008	0.76	0.46	0.11	0.567	0.684	0.905
D	2	17.322	3.3934	0.0069	8.666	1.6967	0.0035	8.27	3.19	0.45	0.108	0.239	0.692
E[b]	2	236.076	0.4175	0.0030	118.038	0.2088	0.0015	112.66	0.39	0.20	0.009	0.718	0.837
F	2	0.114	0.7214	0.0056	0.057	0.3607	0.0028	0.05	0.68	0.36	0.949	0.596	0.734
G	2	16.044	1.4575	0.0169	8.022	0.7287	0.0085	7.66	1.37	1.09	0.116	0.422	0.479
H	2	5.566	0.5237	0.0048	2.783	0.2618	0.0024	2.66	0.49	0.31	0.274	0.670	0.764
e	2	2.095	1.0631	0.0155	1.048	0.5315	0.0078						
T	17	360.287	10.8204	0.0600									

[a] When $Pr < 0.05$, this indicates that the effect is significant at $\alpha = 0.05$.
[b] $F_{0.05;1,2} = 18.51$; $F_{0.05;2,2} = 19.0$.

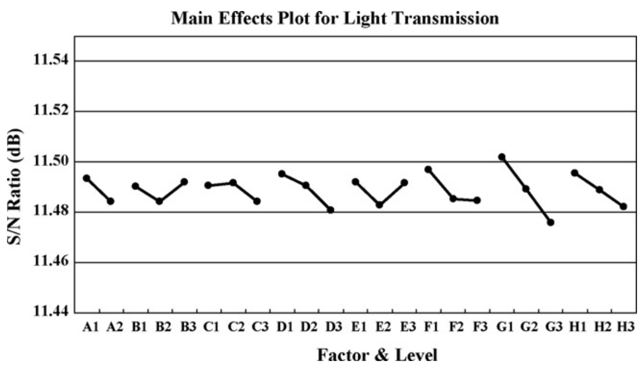

Fig. 5 – Response diagram for light transmission in the Taguchi experiments.

2.5. *Confirmation experiments*

In order to verify the validity of the results of the Taguchi experiments, confirmation experiments are executed at the optimum combination of factor levels (Peace, 1993). Firstly, the significant factors are chosen from process parameters based on the prediction of S/N values at optimum combination of factors. The optimum combination of parameters, based on surface waviness of lenses, is $A_1B_3C_2D_3E_3F_3G_3H_1$. The most significant factor is E (packing pressure), followed by A (melt temperature), D (injection pressure), and G (mold temperature). Hence the confirmation experiments, for surface waviness of lenses, are implemented based on control factors A, D, E and G. The results of the confirmation experiments for optimum factor combination are then compared with the predicted value to verify the validity of the Taguchi experiments. The average of S/N ratio is 10.96 dB, by the Taguchi L18 experiments. The prediction value for S/N ratio at the optimum combination of factor levels (Peace, 1993) is

$$\hat{\eta} = \bar{T} + (\bar{A}_1 - \bar{T}) + (\bar{D}_3 - \bar{T}) + (\bar{E}_3 - \bar{T}) + (\bar{G}_3 - \bar{T}) \tag{3}$$

The calculated value for the predicted S/N ratio is 19.84 dB at the optimum combination, corresponding to a surface waviness of 0.1018 μm.

The confidence interval is also calculated based on the S/N prediction in the confirmation experiments. A confidence interval of 2.59 dB for a predicted S/N ratio of 95% ($\alpha = 0.05$) is obtained after five repeated confirmation experiments at the optimum condition. The range of the S/N ratio falls within a range of 9.84 ± 2.59 (17.25–22.43) dB, corresponding to a surface waviness of 0.1018 ± 0.031 (0.0756–0.1372) μm. Table 4 lists the results of confirmation experiments based on an optimum combination of factor levels. The results show that both the experimental data and the S/N ratios fall within the confidence interval. However the validity of the optimum combination of parameters derived from the Taguchi experiments was confirmed.

2.6. *Full factorial experiments*

The significant factors regarding surface waviness for full factorial experiments are screened from the injection process parameters through the Taguchi experiments. In fact, packing pressure and melt temperatures are the only significant parameters in these screening tests. The precision requirements of optical lenses are very strict. Even though mold temperature and injection pressure data did not reach the significant level, the analysis suggested a considerable amount of influence on the result. Therefore, in this paper these two parameters were incorporated into the full factorial experiments for surface waviness. In summary, the experimental factors influencing surface waviness for full factorial design are melt temperature, mold temperature, injection pressure and packing pressure. The experiments were executed at three different levels for each control factor, and the placement of factor levels are listed in Table 5. On the other hand, the quality characteristics discussed are based on the surface waviness of lenses. A total of 81 experiments were implemented, with three separate tests for each factor level, and the average of the three specimens is taken as the waviness value.

Table 4 – Comparison with the result of waviness for the confirmation experiments

Predicted	Experimental	
	Data	Average
S/N ratio (dB)		
19.84 ± 2.59 (17.25–22.43)	19.46	19.348
	19.53	
	19.19	
	19.16	
	19.40	
Waviness (μm)		
0.1018 ± 0.031 (0.0756–0.1372)	0.1064	0.1078
	0.1055	
	0.1098	
	0.1101	
	0.1072	

Table 5 – Parameters and levels of full factor experiments

Control factors	Level		
	1	2	3
(A) Melt temperature (°C)	215	225	235
(B) Injection pressure (MPa)	60	70	80
(C) Packing pressure (MPa)	90	100	110
(D) Mold temperature (°C)	110	120	130

3. Regression analysis

Regression analysis is used to identify the relationship between independent variables and the associated dependent variables, and to predict the trend of dependent variables as a function of independent variables (Chapra, 2005). In this paper, the process parameters are independent variables, whereas surface waviness of lenses is the dependent variable. The regression analysis is implemented based on the results of full factorial experiments and the correlation coefficient R^2 (R-squared) criteria is used to justify the validity of regression

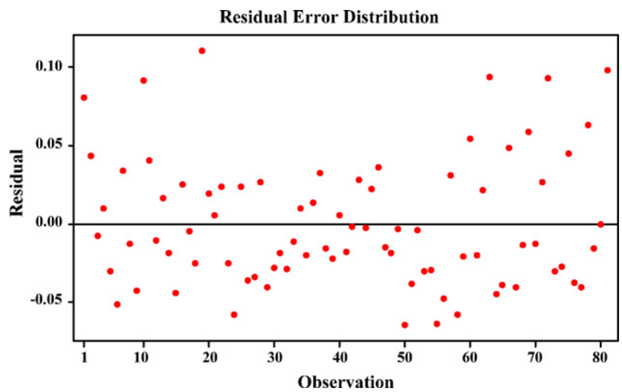

Fig. 6 – Distribution of residual error.

model. R^2 can be written as

$$R^2 = \frac{\text{Sum squared residual (SSR)}}{\text{Sum squared total (SST)}} = 1 - \frac{\text{Sum squared error (SSE)}}{\text{Sum squared total (SST)}} \quad (4)$$

The regression analyses on process parameters and surface waviness of experiments are performed in a commercial software SPSS.

3.1. *Linear regression analysis*

Fig. 6 shows the residual error distribution for full factorial experiments. No apparent deviation of points is observed in data distribution, suggesting a normal distribution of empirical results is as assumed. Furthermore, with the absence of linear correlation among process parameters, a regression model can be formulated for the full experimental data.

Linear regression analysis is first executed, and the linear regression model obtained is

$$\begin{aligned}\text{Waviness} = 7.13 &- 4.45 \times (\text{melt temperature}) \\ &- 0.22 \times (\text{mold temperature}) \\ &- 0.52 \times (\text{injection pressure}) \\ &- 1.98 \times (\text{packing pressure}) \end{aligned} \quad (5)$$

The R^2 value of this model is 0.962, implying the existence of a linear relationship between the independent and the dependent variables.

3.2. *Exponential regression analysis*

Exponential regression analysis was then executed, and the regression model obtained is

$$\begin{aligned}\text{Waviness} = 0.12 &\times (\text{melt temperature})^{-10.81} \\ &\times (\text{mold temperature})^{-0.37} \\ &\times (\text{injection pressure})^{-1.21} \\ &\times (\text{packing pressure})^{-4.50} \end{aligned} \quad (6)$$

Table 6 – The factor levels for confirmation experiments

Process parameters	Experimental conditions 1	Experimental conditions 2
Melt temperature (°C)	220	230
Mold temperature (°C)	65	75
Injection pressure (MPa)	95	105
Packing pressure (MPa)	115	125

The exponential regression model has an R^2 value of 0.969, and hence is a better model than linear model.

3.3. *Nonlinear regression analysis*

The results of linear regression analysis suggest a nonlinear correlation among experimental parameters. A nonlinear regression model is required for processes having apparent interaction among parameters. In this study, a polynomial is used to perform the nonlinear regression analysis, and the regression model obtained is

$$\begin{aligned}\text{Waviness} = 42.22 &- 41.44(X_1) - 0.22(X_2) - 17.48(X_3) \\ &- 28.06(X_4) + 11.50(X_1 \times X_3) + 18.79(X_1 \times X_4) \\ &+ 6.79(X_3 \times X_4) - 5.79(X_1 \times X_3 \times X_4) + 7.33(X_1)^2 \\ &+ 2.64(X_3)^2 + 3.77(X_4)^2 \end{aligned} \quad (7)$$

where X_1, X_2, X_3, and X_4 are the melt temperature, the mold temperature, the injection pressure and the packing pressure, respectively.

The nonlinear regression model has an R^2 value of 0.995, and is superior to both linear and exponential models.

4. Verification of regression models

Confirmation experiments are executed at a different set of parameters to verify the accuracy of the regression models obtained. The factor levels for confirmation experiments are listed in Table 6.

The error between the data of confirmation experiments and the prediction value of the regression model is evaluated by the following equation

$$\text{Error}\,(\%) = \left| \frac{\text{Experimental results} - \text{Predictions}}{\text{Experimental results}} \right| \times 100\% \quad (8)$$

The root-mean-square error (RMSE) of confirmation experiments is a measure of the accuracy of regression models. The definition of root-mean-square error is

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (\text{Error})_i^2}{N}} \quad (9)$$

where N is the number of confirmation experiments.

The errors are calculated from data of confirmation experiments and their corresponding predicted values by regression models (Table 7). The average errors are 10.38%, 8.89% and 4.24%, and root-mean-square errors are 13.12%, 10.67% and

Table 7 – Comparison of errors in confirmation experiments with the prediction of regression models

	R^2	Error (%)	RMSE
Linear	0.962	10.38	13.12
Exponential	0.969	8.89	10.67
Nonlinear	0.995	4.24	5.29

5.29%, for linear, exponential and nonlinear models, respectively.

The results of confirmation experiments revealed that both average errors and root-mean-square errors are smallest for nonlinear models, followed by exponential and linear models. The nonlinear regression is hence a pertinent model for the prediction of behavior of the process. Meanwhile, observations on coefficients of the nonlinear model revealed an interaction between process parameters of injection molding and surface waviness of optical lenses. Therefore, the nonlinear regression model is demonstrated to be the superior model for the process.

5. Conclusion

In this study, a two-stage experimental process is designed to investigate the effects of process parameters on quality characteristics of injected optical lenses. In the first stage, significant factors are identified through the Taguchi screening procedure. The significant factors are then used to implement the full factorial experiments in the second stage. Various regression models are determined and the predicted values are compared with experimental data for confirmation. Several observations can be drawn:

(1) The surface waviness of optical lenses is apparently effected by injection molding process parameters. Surface waviness of lenses can be improved with higher melt temperature, injection pressure, packing pressure and mold temperature. The most significant factor is the melt temperature, followed by packing pressure, injection pressure and mold temperature.
(2) The roughness of a lens is actually a replication of the insert surface, and is not a function of process parameters. Also, process factors have only marginal effect on light transmission of lenses.
(3) Among the regression models for the surface waviness of lenses, the nonlinear equations had the highest accuracy, followed by exponential and linear models. A root-mean-square error of 5.29% and R^2 of 0.995 was observed for the nonlinear regression model. The coefficients of the model revealed the presence of interaction between surface waviness of lenses and injection process parameters.
(4) The statistical model achieved in this study serves as a prediction scheme for surface waviness of lenses as a function of process parameters at a wider range and with a higher reliability.

However, this study only targeted the optimization of a single quality characteristic. Optimizing multiple quality characteristics may involve some complicated considerations, such as the scale, contradiction and units of quality characteristics. Therefore, the most desirable approach is to normalize the parameters and quality characteristics, and convert them into dimensionless entities. The problem is then solved by using multi-objective optimization methods to obtain nonlinear models with multiple quality characteristics.

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