OPTIMIZATION OF INJECTION MOLDING PARAMETERS FOR LED LAMPSHADE

Kingsun Lee[1] and Jui-Chang Lin[2]
[1]*Department of Mechanical Engineering, ChienKuo Technology University, 500 Changhua, Taiwan*
[2]*Department of Mechanical Design Engineering, National Formosa University, 632 Huwei, Yunlin, Taiwan*
E-mail: kingsun@ctu.edu.tw; nhit100@gmail.com

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ABSTRACT

The unibody of LED (light-emitting diodes) lampshades is fabricated by injection mold; the forming technique is complicated, especially for multi-cavity molds. This study applies a finite element analysis to explore the influences of the shrinkage of LED lampshades. The effect of selected injection parameters and their levels on shrinkage size, and the subsequent design of experiments were accomplished using the Taguchi method. The results were confirmed by experiments, which indicated that the selected injection parameters effectively reduce the shrinkage. The error between optimal estimated value and verified value is within 3.82%.

Keywords: micro injection; LED lampshade; shrinkage; Taguchi method.

OPTIMISATION DES PARAMÈTRES DE MOULAGE PAR INJECTION POUR ABAT-JOURS LED

RÉSUMÉ

Les abat-jours monocoques LED (diode électroluminescente) sont fabriqués par moule à injection ; la techniques de préforme est compliquée, surtout pour les moules à cavités multiples. La présente recherche s'intéresse à l'application de la méthode d'analyse des éléments finis pour explorer les influences des rétrécissements sur l'abat-jour LED. L'effet des paramètres d'injection sélectionnés et le niveau d'ampleur du rétrécissement, ainsi que la conception subséquente des expériences ont été accomplis selon la méthode Taguchi. Les résultats ont été confirmés par des expériences, lesquelles ont indiqué que les paramètres d'injection sélectionnés réduisent efficacement le rétrécissement. L'erreur entre la valeur optimale estimée et la valeur vérifiée est en dedans de 3.8%.

Mots-clés : micro-injection ; abat-jour LED ; retrait ; méthode Taguchi.

1. INTRODUCTION

Injection molding is one of important process in the industry; it possesses high production rate, shorter molding cycle, low waste rate, smooth surface and complicated shape. Many defects resulted in poor quality of products, such as short shots, shrinkage, warpage and residual stress during injection molding process. Faced with increasing complexity of product design and the high requirement of quality in injection molding industry, using the trial-and-error approach to determine the process parameters for injection molding is not a smart way. Good mold design and optimal process parameters are the key influences of productivity, quality, and cost of production.

The process of injection molding can be divided into three stages: (1) during the filling stage, the mould cavity is filled with molten plastic fluid under high pressure; (2) after the mold cavity is completely filled, it is necessary to deliver more plastic fluid for compensation of shrinkage of plastic, ensuring the cavity is properly filled; and (3) cooling and removing of the products.

The Newton fluid model is the simplest filling model. Richardson [1] was the first to propose the comprehensive and detailed concept in flow filling. The major concept was based on the relationship of lubrication theory. The 3D flow theory was simplified to a 2D Hele–Shaw flow theory. For sufficiently simple initial domains D_0 these allow the problem to be reduced to the solution of a finite system of algebraic equations. For more complex initial domains an approximation scheme leads to a similar system of equations to be solved.

In fact, Bird [2, 3] assumed that the plastic material was a Newton fluid, and observed a Newton fluid model flow in the mold cavity. He speculated and derived mold flow theory based on this fact. When the shape of the mold is complicated and varies in thickness, then the equation becomes non-linear and we're unable to analyze. Thus, finite difference and numerical method should be used to solve the problems [4, 5]. Because the polymer was viscoelastic properties of fluid, it is an optimal tool to utilize viscoelastic formula to solve the problem of fluidity. Goyal et al. [6] used the White–Metzner viscoelastic model to simulate flowing conditions of disk mold center pouring. When Goyal solved these governing equations using the finite difference method, he found that the influence of viscoelastic makes no change to temperature distribution, but that it imposed a significant impact to the stress range. Assuming it is viscoelastic fluid model, the popular Generalized Newtonian Fluid (GNF) model was generally used to simulate the flowing activity. Thus, the finite difference and GNF model are very suitable for numerical simulation; the simulated results are very close to the actual conditions.

Jansen et al. [7] systematically analyzed shrinkage effects of injection parameters in seven types of thermo plastic materials (PC, PS, ABS, HIPS, PBT 1505, PBT 3235, HDPE). It turned out that the holding pressure was the key parameter. The effect of the melt temperature is slightly less important. Injection speed and the mold temperature have relatively small effects.

Chang [8] systematically researched shrinkage conditions of three plastic materials (HPDE, GPS, ABS) in the injection process using the Taguchi Method. He found that mold temperatures, melt temperatures, holding pressure, and holding time have the most effects on these three materials. The optimal conditions for reducing shrinkage identified by the Taguchi method are experimentally verified and validated by t-statistic tests.

Huang and Tai [9] studied factors affecting the warpage of thin-shell injection parts using the C-Mold and the Taguchi methods. The results showed that the holding pressure has the most effect, followed by mold temperatures, melt temperatures, and holding time. In addition, applying the experimental design of Taguchi method is a quite effective method to deduce the optimum set of effective factors in injection molding to produce plastic parts with minimum warpage.

Hsu [10] used the Moldflow software to conduct a simulation analysis on aspheric lenses. In addition, the Taguchi Method was used to find the effect of molding conditions to the shrinkage of aspheric lenses.

The results indicated that holding pressure, filling duration, and gate size have significant effects on the volumetric shrinkage rate. Multi-step holding pressure and a slower flow rate were found to be helpful in reducing the rate of volumetric shrinkage.

Chen et al. [11] proposed a LED lens design optimization system using Taguchi methods, and the Back-Propagation Neural Network (BPNN) was used to establish the LED lens quality predictor to predict the viewing angle and luminance uniformity in different overall sizes. The Genetic Algorithm (GA) with the quality predictor was used to find out the optimum design parameter combination of overall size according to the required quality objective. A LED optical lens with a 135° FWHM angle and a 93.35% uniformity was designed by this approach.

Liu [12] used FEM to analyze the LED lamp heat sink, the length, width and numbers of the heat sink fins being design variables, and the maximum junction temperature of LED being the objective function. The results show that the conditions of the LED chip junction temperature do not exceed 60°, and the heat sink structure optimized values were the following: fin length is 62.5 mm, fin width is 1 mm, and the number of fins is 20.

Numerical simulations are very important tools in science and engineering for the analysis of mold flowing; the Taguchi method is very popular for solving optimization. Therefore, this study applies finite element analysis to explore the influences of the shrinkage of LED lampshade. The 3D model is built to simulate injection conditions, the effect of selected injection parameters and their levels on shrinkage size, and the subsequent design of experiments were accomplished using the Taguchi technique. A statistical analysis of variance (ANOVA) is employed to indicate the impact of injection parameters on shrinkage. The results can be used in industrial applications to produce high quality of LED lampshade.

2. THEORY

2.1. Governing Equations

This study assumed that the plastic was an inelastic non-Newtonian fluid in the melting state. Its viscosity could be described as a power-law fluid. It was also assumed that the plastic was very thin (with a thickness to length/width ratio of $< 1:10$). Compressible GHS (Generalized Hele–Shaw) was used to describe plastic flow.

The 3D flow activity inside the mold can be described by the following conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho u = 0, \tag{1}$$

$$-\nabla P - \nabla \cdot (\mu \dot{\gamma}) = 0, \tag{2}$$

$$\rho \frac{\partial u_i}{\partial t} = -\frac{\partial P}{\partial x_i} + \left[\sum_{j=1}^{3} \frac{\partial \tau_{ji}}{\partial x_j} \right], \tag{3}$$

$$\rho C_p \left[\frac{\partial T}{\partial t} + u \cdot \nabla T \right] = \nabla (k \nabla T) + \eta \dot{\gamma}^2, \tag{4}$$

$$\rho C_p \frac{\partial T}{\partial t} = k \nabla^2 T, \tag{5}$$

where ρ is density, u is velocity vector, T is temperature, t is time, p is pressure, τ is shear stress, μ is viscosity, k is thermal conductivity coefficient, C_p is specific heat, $\dot{\gamma}$ is shear rate.

Equations (1–5) represent the simplified governing equations to the modeling of the mold-flow processes. The homogenous mold temperature and the sequence of filling following the optimized injection molding designs will affect the shrinkage of the molded product.

Table 1. Control factors and levels.

Factors	Level 1	Level 2	Level 3	Level 4
A: Mold temperature (°C)	110	115	120	125
B: Melt temperature (°C)	270	280	290	300
C: Pack pressure (kg/cm^2)	60	80	100	120
D: Pack time (sec)	1	2	3	4
E: Cooling time (sec)	90	100	110	120

2.2. Taguchi Method

The Taguchi method was created by Genichi Taguchi in 1949. It is an engineering methodology for obtaining the relationship between products and manufacturing process.

The Taguchi method is an important tool for robust design, combining experimental design theory and the concept of quality loss function. It offers a simple and systematic approach to optimize performance design, quality and cost [13–15]. Taguchi's approach is based on statistical design of experiments, which fulfills the requirements to solve engineering problems and enhance process optimization. Taguchi suggests analyzing variation using an appropriately chosen signal-to-noise ratio (S/N). These S/N ratios are derived from the quadratic loss function. The Taguchi analysis of the S/N ratio involves three kinds of quality characteristic, including the-nominal-the-better, the-smaller-the-better, and the-larger-the-better. To obtain optimal molding performance, the-smaller-the-better quality characteristic for shrinkage must be taken; it can be expressed as

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right), \tag{6}$$

where y_i is the observed data. Regardless of the category, n is the number of tests in a trial, a greater S/N ratio corresponds to a better performance. The level of a factor with the highest signal-to-noise ratio is the optimum level [16].

2.2.1. Experimental design

The Taguchi method uses a practical design of orthogonal arrays and a relatively small number of experiments to find one set of optimization. This experiment involved five factors: melt temperature, mold temperature, pack time, pack pressure and the cooling time. Each factor was used at four levels. Table 1 lists the experimental factors and levels.

The Taguchi method experiments were used to investigate the relationship between injection processing parameters and shrinkage in this study. Table 2 lists the orthogonal array; each experiment has seven experimental data, and the S/N ratio is calculated using Eq. (6).

3. SIMULATION AND ANALYSIS

The material used in this experiment is polycarbonate (PC) resin from CHI MEI Co. (Taiwan). The mechanical properties of PC resin are listed in Table 3. Modex 3D professional analytic software is applied in mold flow analysis, the analytic mesh model is shown in Fig. 1.

Optimum design of a gate and balanced runner system is necessary for injection molds, so that melted plastic flowing conditions are the same or very similar during filling phase. The dimensions of runners are very important for filling the cavity with melted plastic of enough high temperature and pressure. The gate position also plays a key role because it influences the location of weld lines in a product and it should be designed carefully to obtain a good quality of the products.

Table 2. Orthogonal array L_{16} (4^5).

Set No.	Control factors					S/N
	A	B	C	D	E	
1	1	1	1	1	1	1.6
2	1	2	2	2	2	7.56
3	1	3	3	3	3	–3.94
4	1	4	4	4	4	–5.36
5	2	1	2	3	4	3.25
6	2	2	1	4	3	9.16
7	2	3	4	1	2	–3.52
8	2	4	3	2	1	–4.78
9	3	1	3	4	2	5.68
10	3	2	4	3	1	8.83
11	3	3	1	2	4	–2.62
12	3	4	2	1	3	1.18
13	4	1	4	2	3	10.57
14	4	2	3	1	4	7.42
15	4	3	2	4	1	–1.28
16	4	4	1	3	2	–0.83

Table 3. Mechanical properties of PC resin.

Specifications	Units	Values
Tensile strength	kg/cm^2	630
Bending strength	kg/cm^2	920
IZOD impact strength	kg-cm/cm	87
Melt temperature	°C	150
Melt flow rate	g/10 min	10.0

The LED lampshade was an injection molded part with a thick shell. It was easily affected by cold mold wall and led to heat loss, and consequently short shots were occurred. Therefore, the main factors of short shots were subject to mold temperature and plastic temperature. The mold had to maintain a uniform temperature in the range of 110 to 130°C by using hot oil through the mold to prevent short shots.

The packing pressure directly affected the shrinkage of plastic after filling phase. The results of shrinkage distribution indicated that large shrinkage was presented on the far area of the gate while packing pressure was small, packing pressure can be considered as one of significant influencing factors for the shrinkage of the plastic.

The analytical results of shrinkage, temperature, deflection and residual stress are shown in Figures 2–5; an unbalanced cooling process will result in deflection, residual stress and shrinkage of plastic parts.

4. RESULT AND DISCUSSION

4.1. Optimal Parameters Combination

This study attempts to investigate the flowing conditions of the melted polymer using mold flow analysis software and Taguchi method. The simulation results of injection molding show that numerous factors affect the shrinkage, warpage and shear stress in molding process, such as mold design, product design, molding processing and the characteristic of the material and so on. Especially, the melt, solidification, crystal molecules orientation and residual stress of the material are shown to have a significant effect on warpage and shrinkage.

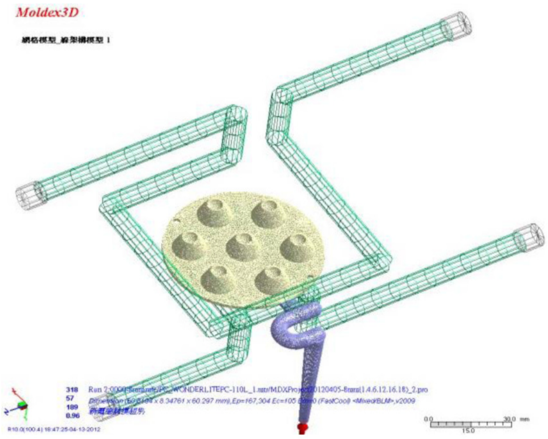

Fig. 1. Mesh model of injection molding.

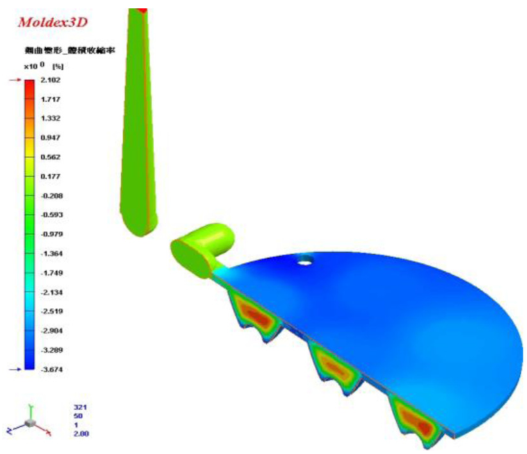

Fig. 2. Volumetric shrinkage.

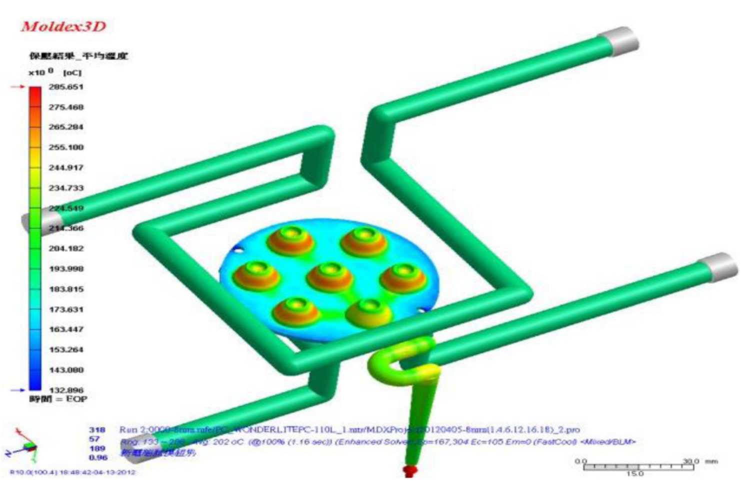

Fig. 3. Temperature distribution.

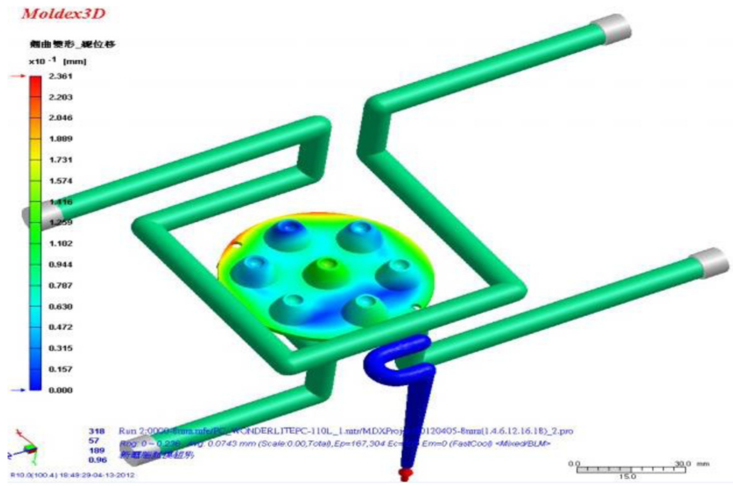

Fig. 4. Deflection distribution.

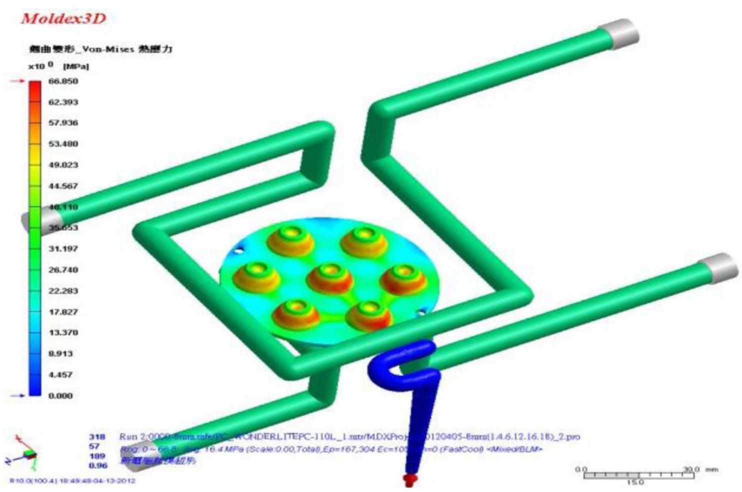

Fig. 5. Residual stress.

A set of experiments using the Taguchi method was conducted to investigate the relationship between injection processing parameters and shrinkage. The-smaller-the-better quality characteristic for minimum shrinkage should be used to obtain optimal injection molding performance.

Optimal process design is achieved when the S/N ratio is maximized. After computation of the shrinkage, S/N ratios for each experiment of L_{16} (4^5) were calculated by applying Eq. (6).

The effect of each control factor (A to E) on the shrinkage was analyzed from the S/N ratio response table (Table 4), which expresses the S/N ratio at each level of control factor. The control factor effect is determined by its level difference values. A bigger control factor level difference results in a greater effect on the shrinkage at the injection processing. The effect of all control factors and level differences can be calculated, as indicated in Table 4. Factor B (melt temperature) is the most effective process factor, because it has the highest level difference among all control factors.

Figure 6 shows response diagrams for all control factors of the injection molding process. The response diagram shows more clearly the effect of each control factor. The slope of the oblique line determines the effect of the control factor. The response diagram can determine the best-quality characteristics. Selected

Table 4. S/N ratio response for shrinkage.

Level	A	B	C	D	E
1	–0.04	5.27	1.82	1.67	1.09
2	1.03	8.24	2.68	2.68	2.22
3	3.27	–2.84	1.09	1.83	4.24
4	3.97	–2.45	2.63	2.05	0.67
Effect	4.01	11.08	1.59	1.01	3.57
Rank	2	1	4	5	3

Table 5. Optimal process parameters.

Factors	Level
A: Mold temperature (°C)	125
B: Melt temperature (°C)	280
C: Pack pressure (kg/cm^2)	80
D: Pack time (sec)	2
E: Cooling time (sec)	110

Table 6. Confirmation test results.

Trial No.	Calculated value S/N ratio	Confirmation test S/N ratio %	Error
1	13.59	13.65	1.76
2		13.07	3.82

factors with higher S/N ratio values will yield minimum value of shrinkage. The optimal injection molding parameters for a minimum shrinkage were A4, B2, C2, D2 and E3 as shown in Table 5.

A confirmation test was done after the optimal combination of process parameters was determined. The confirmation test was a repetition of the main experiment that involved injection molding using optimal control factors to obtain the predicted quality characteristics:

$$\bar{\eta}_{\text{opt}} = \bar{\eta}_{\text{ave}} + (\bar{\eta}_{Ai} - \bar{\eta}_{\text{ave}} + \cdots + \bar{\eta}_{Di} - \bar{\eta}_{\text{ave}}), \tag{7}$$

where $\bar{\eta}_{\text{opt}}$ is the S/N ratio of optimal process conditions; $\bar{\eta}_{\text{ave}}$ is the average S/N ratio of all control factors; and $\bar{\eta}_{Ai}$ is the S/N ratio when factor A is at optimal level i.

Two trials were made in the confirmation test; the results of confirmation test are presented in Table 6. The table shows an error between the values obtained in the confirmation test and the calculated values (Eq. 7) of the S/N ratios, the error is within 3.82%. Furthermore, the confirmation test verifies that the obtained optimal injection parameters provide high experimental reliability. Figure 7 shows the injection molded part from confirmation test. The minimum shrinkage is within 0.03 mm while the optimal parameters are utilized in injection molding.

4.2. Analysis of variance (ANOVA)

ANOVA was used to analyze results of parameter design. In this study, ANOVA established the relative significance of factors in terms of their percentage contribution to the response. The important process parameters with respect to the shrinkage were investigated. The percentage contribution of variance can be calculated, as shown in Table 7.

An estimate of the sum of squares for the pooled error was obtained. Therefore, it was necessary to pool the less important factors for correct interpretation of results. From Table 7, it can be observed that

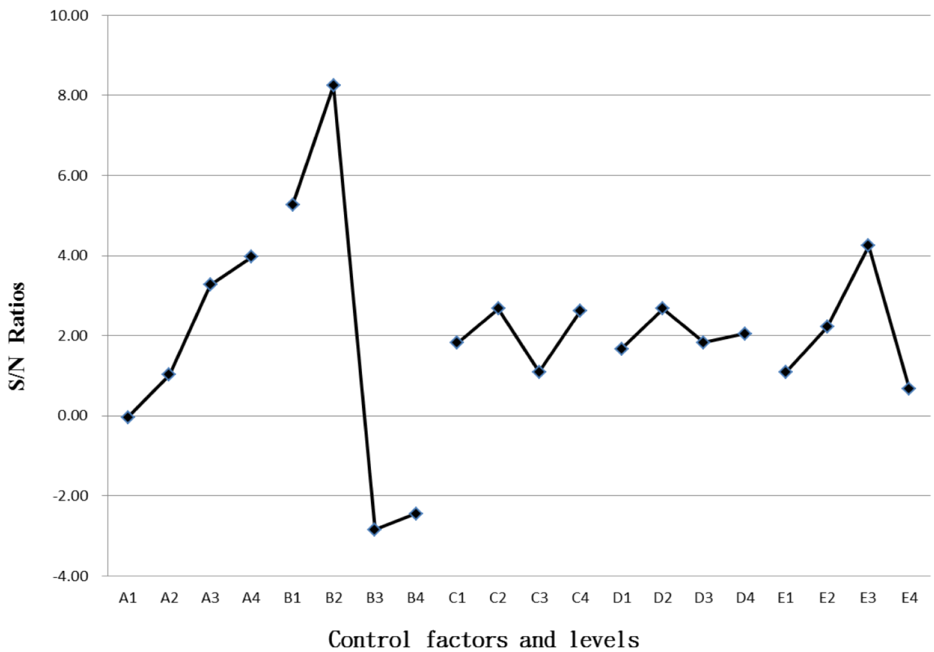

Fig. 6. Response diagram for shrinkage.

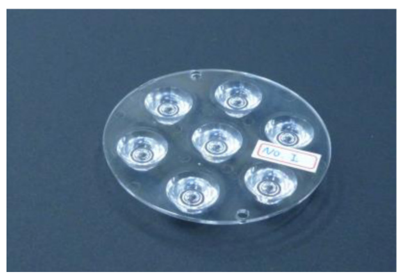

Fig. 7. Confirmation test product.

Table 7. ANOVA analysis.

Sources of Variance	Sum of Squares (SS)	Degrees of Freedom (DOF)	Variance (Var)	F-ratio	Pure SS (%)	Contribution (%)	Confidence*
A	1.5996	3	0.5332	4.6649	1.2567	1.65	99.62
B	58.4361	3	19.4787	170.4173	58.0932	76.08	100.00
C	3.5768	3	1.1923	10.4313	3.2339	4.24	100.00
D	1.4305	3	0.4768	4.1715	1.0876	1.42	99.29
E				Pooled			
Pooled error	11.3167	99	0.1143			16.62	
Total	76.3597	111					

*At least 99% confidence.

cooling time (factor E) is pooled as error due to a small sum of squares and F-ratio. An F-ratio value at 99% confidence level is used to decide the significant factors affecting the quality characteristic. The melt temperature (factor B) is the most significant factor, indicated by its contribution of a greater percentage.

The calculation of ANOVA was made on the basis of the equations in [16]. The total sum of the squared deviations SST is decomposed into two components: the sum of the squared deviations SSm due to each factor and the sum of the squared error SSe.

In ANOVA, total sum of squares (SST) can be calculated as:

$$\mathrm{SST} = \sum_{i=1}^{n} \sum_{j=1}^{r} Y_{ij}^2 - nr\bar{Y}^2, \tag{8}$$

where Y_{ij} is the experimental data, n is the number of experiments, each experiment has r experimental data, $\bar{Y}$ is the grand mean.

The sum of squares (SS) for each factor m can be expressed as:

$$\mathrm{SSm} = \frac{nr}{L} \sum_{k=1}^{L} (\bar{Y}_k - \bar{Y})^2, \tag{9}$$

where $\bar{Y}_k$ is the response values at level k of factor and L is the number of levels.

$$\text{Total Degrees of freedom (DOF)} = \text{Total number of experiments} - 1 \tag{10}$$

$$\text{DOF for each factor} = \text{Number of levels}(L) - 1 \tag{11}$$

$$\text{Variance (Var) = SS/DOF} \tag{12}$$

$$\text{F-ratio = Var/Var of error (Ve)} \tag{13}$$

$$\text{Pure sum of square = SS-Ve} * \text{DOF} \tag{14}$$

$$\text{Percentage Contribution = Pure SS/Total SS} \tag{15}$$

5. CONCLUSIONS

This study applied the Taguchi method on injection molding of LED lampshade to optimize injection parameters with the aim of reducing the shrinkage. This result satisfies the required standard for LED factory production, and provides practical assistance to engineers in selecting a suitable parameter for injection molding. The experimental results may be summarized as follows:

1. Optimum processing design of LED lampshade tended to obtain minimum shrinkage during cooling and shrinkage stage. The minimum shrinkage is within 0.03 mm.
2. ANOVA verified that factor B is very significant for injection LED lampshades. Factors E had less influence and were pooled as error.
3. The optimal combination of injection parameters was confirmed through confirmation experiments. The results indicate that the error between confirmation tests and predicted values was within 3.82%.

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