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Optimization of Injection Molding Processing Parameters for LCD Light-Guide Plates

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Liquid crystal display (LCD) light-guide plate injection molding has always had the unexpected deformation issue which results in variations in the quality of the resulting products. The main cause for this lies in the setting of the processing parameters. The objective of this paper is to combine grey relational analysis (GRA) with the Taguchi method to optimize multiple-quality injection molding processing parameter combination. First, a $L_{18}(2^1 \times 3^7)$ orthogonal array was used to plan out the processing parameters that would affect the injection molding process. Then GRA was applied to resolve the drawback of single quality characteristics in the Taguchi method, and then the optimized processing parameter combination was obtained for multiple quality characteristics from the response table and the response graph from GRA. The quality characteristics of this experiment were the depth and angle of the light-guide plate V-cut microstructure. Signal-to-noise ratio (SN ratio) calculation and analysis of variance (ANOVA) would be performed to look into the results obtained from the experiment. From ANOVA the significant factors could be obtained which had the greatest effect on the light-guide plate quality characteristics, in other words, by controlling these factors, the quality characteristics of the LCD light-guide plate could be effectively controlled. Finally, the reliability and reproducibility of the experiment was verified by confirming a confidence interval (CI) of 95%.

Keywords grey relational analysis, injection molding, light-guide plate, multiple quality characteristics, Taguchi quality method

1. Introduction

Since liquid crystal is a chemical material which does not possess luminescence characteristics, the broadly utilized liquid crystal display (LCD) panels currently used all need to depend on an additional light source to display images. Therefore, the backlight module has become an indispensable component in the LCD panel. Through the sufficient, uniform, and even illumination provided by the backlight module, the best displaying effect from the LCD panel may be obtained. The backlight module is composed of the lamp, light-guide plate, diffuser, prism, reflector, lampshade, and outer structure (plastic frame, metal frame, aluminum frame). The light-guide plate is the main component of the backlight module, and high luminescence is obtained and provided through the microstructure of the light-guide plate. The function of the light-guide plate is to guide the direction of the scattering of light, raising the luminance of the panel, and assuring the even and uniform brightness of the panel. The structure of the backlight module is shown in Fig. 1. Therefore, the quality of the design and production of the light-guide plate has a crucial effect on the brightness of the LCD display panel. This is why the core and most crucial technology for producing a LCD display lies in the technology for producing the backlight module (Ref 1).

Injection molding is one of the best methods for producing a complex-shaped three-dimensional product, and is therefore a crucially important core technology for the production of light-guide plates. However, the specification and setting of the injection-molding processing parameters has always possessed the problem of resulting in the deformation of the light-guide plate because of shrinkage and contraction, causing variations in the quality of the light-guide plates produced. Changes in injection-molding processing parameters such as cooling time, mold temperature, melt temperature, injection speed, injection pressure, packing pressure, packing switching, and packing time have direct impact on the measurements of the V-cut microstructure of light-guide plate. Therefore, in order to obtain optimal processing characteristics when performing light-guide plate injection molding, the suitable processing parameters were often decided in advance. But because of the vast number of processing parameters and their complexity, currently choosing them depends completely on the experience of the person performing the operation, or must be completed by continually correcting the mold and processing parameters through trial and error. This sort of method is not only time consuming, but also increases the time for trying out the molds. It also results in money wastage, and the passing down of previous experience is not easy, because in the injection molding process, there exist many uncertain factors other than the processing parameters, for example, the perturbation of the material, the effects of outside temperatures, etc. All factors that are uncontrollable can and will affect the quality of the product. Therefore, even under identical processing parameters, the quality of the products produced will still vary.

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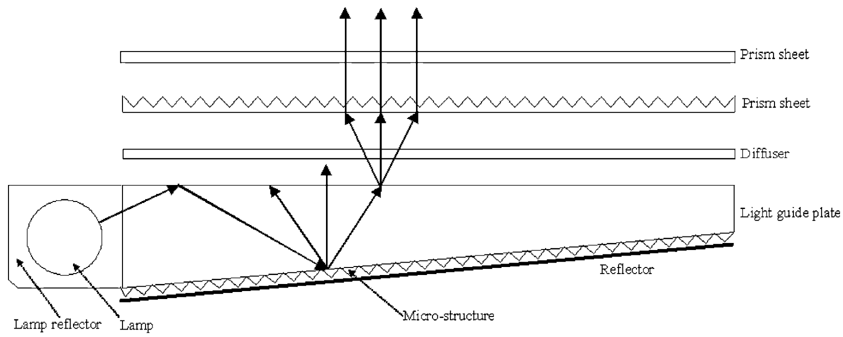

Fig. 1 The structure of the backlight module

According to research made in previous literature, Sanschagrin (Ref 2) stated that injection time, injection pressure, packing pressure, back pressure, clamping pressure, open mold time, screw speed, and shot size, etc., affected the injection molding processing parameters. He pointed out that injection speed and injection pressure had a huge impact on the quality of the product. The injection speed and packing pressure would affect the weight and the amount of shape change. Siegmann et al. (Ref 3) found through experiment that residual stress and mold temperature were highly related, lower residual stress was obtained under higher mold temperatures, inferring that higher mold temperatures mean a smaller temperature difference with the melt, therefore resulting in lesser contraction during the cooling process, and therefore resulting in lesser residual stress in the final product. Experiments also showed that high packing pressure would significantly increase the residual stress in the center region, and the surface layer would drop slightly (Ref 4). Pham et al. (Ref 5) looked into the relation between injection speed and residual stress, discovering that the residual stress in the central region did not have much to do with injection speed, surface stress has a more significant effect. In addition, relatively low and relatively high injection speeds decreased residual stress and medium injection speeds would result in higher residual stress. Jansen et al. (Ref 6) performed experiments on seven common thermoplastic polymers, comparing the effect that processing parameters had on their degree of shrinkage deformation. The results from the experiment showed that packing pressure was a key parameter. Melt temperature was the next important parameter. Choi and Im (Ref 7) analyzed the shrinkage and warpage of the final injection product using numerical analysis methods, taking the residual stress issues in the packing pressure and cooling stages into consideration, and proving through the residual stress curve that the packing pressure stage had the most profound effect on the results of injection molding.

With regard to the vast number of processing parameters, there had been previous studies aimed at using the Taguchi method to find the relationship between processing parameters and the quality of the final product. Ji et al. (Ref 8) used the Taguchi method to plan metal injection molding processing, hoping to find the optimum parameter combustions for high final density. A L_9 orthogonal array was used to plan four sintering factors for the injection molding: sintering temperature, heating rate, sintering time, and sintering atmosphere. The reliability of the experiment was confirmed with a 90% CI. Thian et al. (Ref 9) adopted a L_9 orthogonal array from the Taguchi method to carry out research on the sintering characteristics of Ti-6Al-4V/HA tensile bars. Its final product was produced using powder injection molding. The processing parameters that were looked into include sintering temperature, heating rate, packing time, and cooling rate. From the experimental result, it was found that sintering temperature, heating rate, and cooling rate had a more significant effect on sintering characteristics.

The Taguchi method is used mostly in the optimization of single quality characteristics, but it often fails to represent the optimization of processing parameters for the overall quality. For this reason, Ho et al. (Ref 10) came up with an effective method for the optimization of injection molding processes with Polycarbon-ate/Acrylonitrile-Butadiene-Styrene (PC/ABS) blends. Injection molding parameters including filling time, melt temperature, and mold temperature were all taken into account in the experiment. The results proved that a correction exists in the relationship between GRA and the tensile test of the final product. Therefore, GRA could replace the traditional method which changes one parameter at a time. Li et al. (Ref 11) used GRA in the research of injection molding processing parameter optimization, and was able to obtain the processing parameter factor which had the most significant effect on the final product through the grey relational grades matrix.

Since there are two light-guide plate quality characteristics for this study, namely the V-cut depth and angle, therefore in this study the GRA was applied to integrate multiple quality characteristics, thereby obtaining the optimum light-guide plate processing parameter combination, and achieving the goal of process optimization.

2. Experimental Descriptions

2.1 Research Objectives

Since the refraction index of a light-guide plate is 1.49 and it is greater than outside air, the propagation of light inside a light-guide plate occurs in the form of total reflection, just like that of inside a fiber optic cable. Therefore, to be able to obtain illumination, the smooth characteristics of the light-guide plate's surface must be modified, eliminating total reflection and allowing light to propagate out from the surface. For this reason, the light-guide plate used in this study will be wedge-shaped. Wedge-shaped light-guide plates are the most common shape for light-guide plates. The reason for making the light-guide plates into wedge shape is to eliminate the right

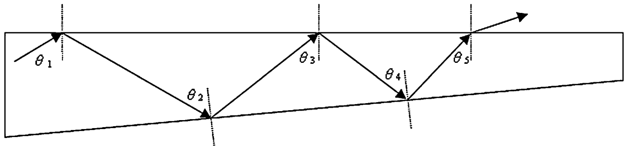

Fig. 2 Wedge-shaped light-guide plate, $\theta_1 > \theta_2 > \theta_3 > \theta_4 > \theta_5$

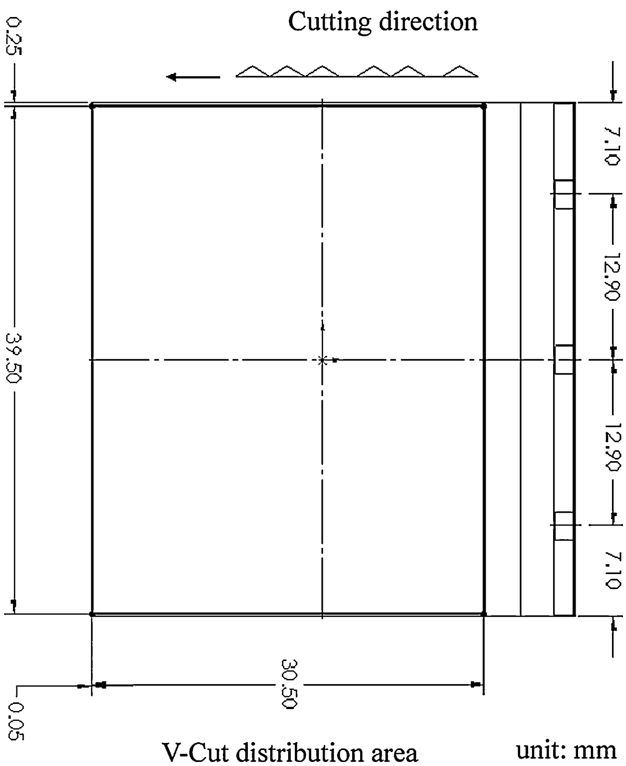

Fig. 3 V-Cut distribution diagram for mold

conditions for total reflection, as shown in Fig. 2. Also, to increase the rate and efficiency of light utilization, thereby increasing the brightness of the LCD panel, the precision machining was applied to create V-cuts on mold by Computer Numerical Control (CNC) machine tools with diamond cutter. Then the mold shown in Fig. 3 with V-cut microstructure was used to mold V-cut light-guide plates by injection-molding machine. The shape and production conditions for the V-cut microstructure are shown in Fig. 4 and Table 1, respectively.

Since the shape and measurements of the V-cut have a direct effect on the brightness of the LCD panel, therefore this study mainly looks into the relationship between light-guide plate processing parameters and quality characteristics, using the Taguchi method and GRA to find the optimum processing parameter combination for light-guide plate processing parameters, with the goal of making the shape and measurements of the light-guide plate V-cut as close to the ideal as possible. First, the quality characteristics are set for the light-guide plate, and then the control factors and their levels are planned out for the processing parameters. After choosing a suitable orthogonal array, the experiments according to the orthogonal array are conducted. Next, ANOVA is performed, at the same time performing relational analysis on double quality characteristics using GRA, and then the optimum light-guide plate processing parameter combination can be obtained through main effect analysis. Finally, a verification experiment is carried out, and the reliability and reproducibility of the experiment are verified with a 95% CI. The steps of the experiment are shown in Fig. 5.

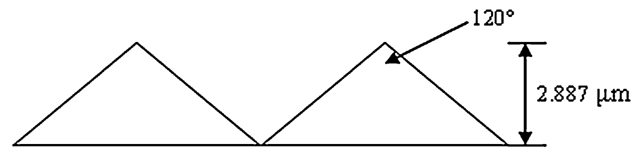

Fig. 4 The shape for the V-cut microstructure

Table 1 The production conditions for the V-cut microstructure

Angle	120°
Height	2.887 μm
Cutting direction	V-cut parallel LED light source

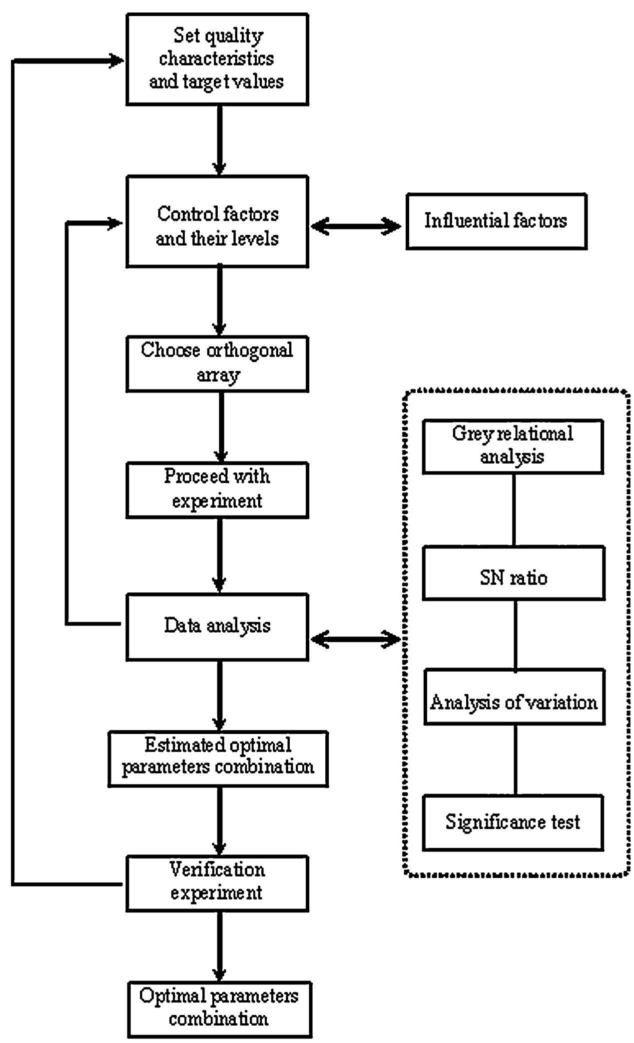

Fig. 5 Experiment procedures

2.2 Materials and Instruments

The molds used in the experiment were provided by Metal Industries Research and Development Center (MIRDC), Taiwan, the upper and lower molds are shown in Fig. 6. The materials used for injection molding are optical grade Poly(methyl methacrylate) (PMMA), serial no. GH 1000S produced by Japan KURARAY Co., Ltd. Before proceeding with injection molding, the materials must first be baked for 4 h at 80 °C to avoid affecting the light penetration rate of the light-guide plate. The injection-molding machine used for the experiment is the Sodick TR30EH, made by Sodick Plustech Co., Ltd, as shown in Fig. 7. The injection molding light-guide plate is shown in Fig. 8. The surface profile measuring system used for measuring the light-guide plate V-cut measurements is the Form Talysurf PGI 635, made by Taylor Hobson Co., Ltd, as shown in Fig. 9.

3. Research Methods

3.1 Taguchi Quality Method

The characteristic of the Taguchi method is to utilize an orthogonal array to plan out the experiment and to use the signal-to-noise ratio (SN ratio) to analyze the data obtained from the experiment. Using an orthogonal array to design the experiment allows the designer to study the effect that multiple control factors have on the average value of quality characteristics and variance quickly and economically, and using SN ratio to analyze the data from the experiment allows the product or process designer to easily find the optimum processing parameter combination. Since the Taguchi quality method can find the factors which affect quality, and obtain processing parameters and data which can improve quality, thereby obtaining the optimum processing parameter combination, therefore this study applies this method to the process of injection molding, to solve the problem of processing parameter optimization, and to improve the quality and production efficiency of injection molding products (Ref 12, 13).

3.1.1 Orthogonal Array. With the orthogonal array we obtain useful statistical information and reliable factor effects with relatively fewer experiments, unlike full factorial experiments which are too repetitious and fractional experiments which are too complex. The orthogonal array chosen for this experiment is $L_{18}(2^1 \times 3^7)$, meaning that there are 18 experiments, one 2-level factor, and seven 3-level factors.

3.1.2 Signal-to-Noise Ratio. When performing experiment design using the Taguchi method, to understand the experiment's performance, a design factor function is usually provided, and it made the standard for our measurement of performance, which is called performance measurement. Taguchi experiment design uses quality loss as a base to design a statistical measurement for the evaluation of performance, called the SN ratio. In this study, the depth and angle of the light-guide plate V-cut directly affects the brightness of an LCD panel, therefore our goal is to make the depth and angle values

Fig. 7 The injection-molding machine

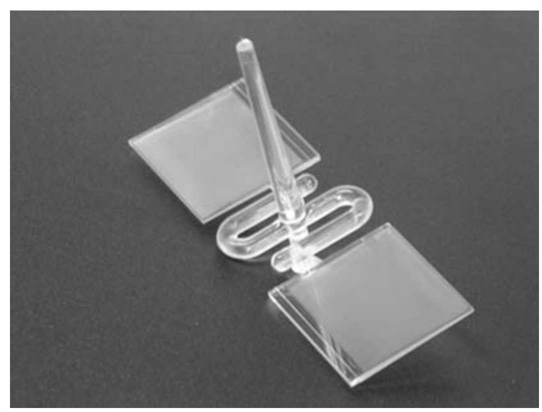

Fig. 8 The injection molding light-guide plate

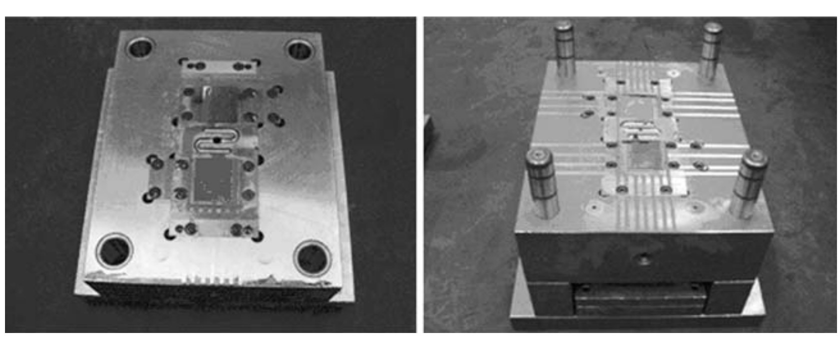

Fig. 6 The upper mold (left) and lower mold (right)

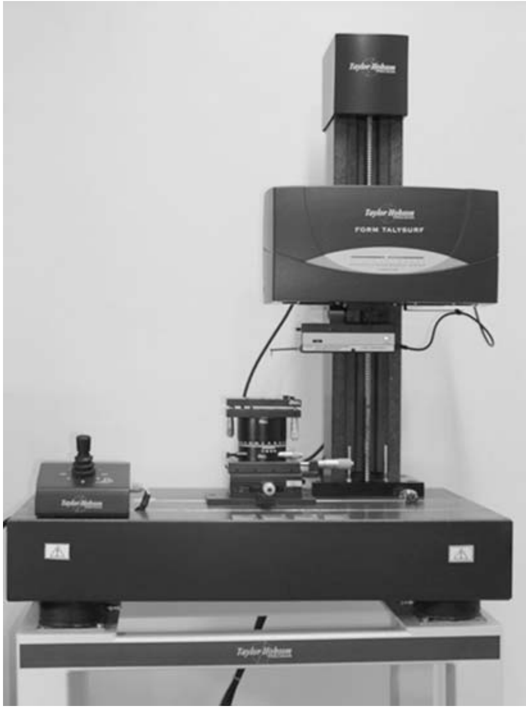

Fig. 9 The surface profile measuring system

of the V-cut as close to our target values as possible. The quality characteristics are chosen to be the smaller-the-better, the SN ratio is

$$\mathrm{SN} = -10\log \mathrm{MSD} \quad \text{(Eq 1)}$$

and the mean squared deviation

$$\mathrm{MSD} = \frac{1}{n}\sum_{i=1}^{n} y_i^2, \quad \text{(Eq 2)}$$

where y_i is the value of the quality measurement and n is the total number of measurements.

3.1.3 Main Effect Analysis. By designing the experiment plan according to the orthogonal array and proceeding with the experiment based on the plan, the data produced by various processing parameter combinations in the orthogonal array can be obtained, and then the establishment of the response table is proceeded with. First, the data obtained from the experiment are calculated into quality indexes (viz., SN ratios), the calculation method depends on the required quality characteristics. After calculating the average response values for each factor level $\overline{F}_i$, then the main effect values are calculated for each factor level ΔF. Next, these data are sorted into a response table, and the effect of each factor is analyzed. If the main effect value of a factor ΔF is large, then that given factor's effect on the system is much greater than that of the other factors. On the other hand, if the main effect value of a factor ΔF is small, much smaller than other factors, then the effect of using this factor to improve quality will not be significant.

$$\overline{F}_i = \frac{1}{m}\sum_{j=1}^{m} y_i \quad \text{(Eq 3)}$$

$$\Delta F = \max\{\overline{F}_1, \overline{F}_2, \ldots, \overline{F}_n\} - \min\{\overline{F}_1, \overline{F}_2, \ldots, \overline{F}_n\}, \quad \text{(Eq 4)}$$

where $\overline{F_i}$ is the mean SN ratio of the ith level of factor F; ΔF is the value of the main effects of factor F; n is the level of the factor; m is the number of level i's in the orthogonal array factor column; and y_i is the SN ratio produced on each i level row.

3.2 Grey Relational Analysis

In the processing parameter analysis of light-guide plates, to study the relationship between the two light-guide plate V-cut quality characteristics obtained by proceeding with the experiment according to the orthogonal array and their target values, a suitable mathematical model must be established to describe it. The first step is to analyze the difference in each light-guide plate quality characteristic caused by each processing parameter, and find their relationships with their target values.

The GRA method used in this paper is brought out by Grey Theory to find the relationship between the V-cut characteristics and their target values in all of the experiments in the orthogonal array.

The GRA of the depth and angle of the light-guide plate V-cut is defined as follows:

The target value of the depth and angle of the V-cut:

Reference sequence $X_0 = (x_0(1), x_0(2))$

The V-cut depths and angles obtained from the various experiments in the orthogonal array

$X_i = (x_i(1), x_i(2)), \quad i = 1, 2, \ldots, 18$

The relation between the target value and the observed experiment value is the correlation coefficient

$$\gamma(x_0(k), x_i(k)) = \frac{\zeta \max\limits_{1\le m\le 18} \max\limits_{k} \Delta_{0,m}(k)}{\Delta_{0,i}(k) + \zeta \max\limits_{1\le m\le 18} \max\limits_{k} \Delta_{0,m}(k)}, \quad \text{(Eq 5)}$$
$$k = 1, 2, \quad i = 1, 2, \ldots, 18$$

is the point relation index of X_i relative to X_0 at point k. $\gamma(x_0(k), x_i(k))$ depicts the degree of correlation of X_0 and X_i at point k, and represents the local characteristic condition of the relation between X_0 and X_i. It is said that the average of $\gamma(x_0(k), x_i(k))$ is the relational grade of X_i relative to X_0:

$$\gamma(X_0, X_i) = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_0(k), x_i(k)) \quad \text{(Eq 6)}$$

The steps for calculating the grey relational grade are as follows (Ref 14)

Step 1: Calculate the initial value item (or average value item) in each sequence

Set $X_i' = X_i/x_i(1) = (x_i'(1), x_i'(2), \ldots, x_i'(n)), \quad i = 0, 1, 2, \ldots, 18$ (Eq 7)

Step 2: Calculate the differential sequence

$$\Delta_i(k) = |x_0'(k) - x_i'(k)|, \Delta_i = (\Delta_i(1), \Delta_i(2), \ldots, \Delta_i(n)),$$
$$i = 1, 2, \ldots, 18 \quad \text{(Eq 8)}$$

Step 3: Calculate the maximum and minimum difference between two levels

$$M = \max_i \max_k \Delta_i(k), m = \min_i \min_k \Delta_i(k) \quad \text{(Eq 9)}$$

Step 4: Calculate the correlation coefficient

$$\gamma_{0i}(k) = \frac{m + \zeta M}{\Delta_i(k) + \zeta}, \ \zeta \in (0,1), \ k = 1,2,\ldots,18, \ i = 1,2,\ldots,18 \quad \text{(Eq 10)}$$

Step 5: Calculate the relational grade

$$\gamma = \frac{1}{n}\sum_{k=1}^{n} \gamma_{0i}(k), \ \ i = 1,2,\ldots,18 \quad \text{(Eq 11)}$$

After entering the target values for the light-guide plate V-cut depths and angles as a reference sequence, the respective relational grades with regard to the observed values obtained from each experiment in the L_{18} orthogonal array can immediately be calculated, and then can be performed analysis using the main effect analysis method. Afterwards the optimum light-guide plate processing parameter combination from the response graph and the response table can be obtained.

3.3 Analysis of Variance

After experiment was made as planned out using the Taguchi method, ANOVA must be performed on the data obtained from the experiment to obtain a complete result. There are two main reasons for performing ANOVA: first is to evaluate the accuracy level of the experiment, second is for significance testing through ANOVA of the data obtained from the experiment. From analysis of variance, subjective evaluation methods can be avoided, and the effects of each of the control factors relative to experimental inaccuracies also can be isolated, describing the importance of each factor using quantitative value and ensuring that no important factors are left out, increasing the precision of forecast and projection.

The formula and method for ANOVA is as stated below:

3.3.1 Degrees of Freedom (DF). The DF for each factor equals its level minus one; the total numbers of DF equal the total numbers of experiments minus one, and the DF for the error equals the total DF minus the sum of the DF for each factor.

3.3.2 Correction Factor (CF).

$$\text{CF} = \frac{1}{n}\left(\sum_{j=1}^{n} y_j\right)^2, \quad \text{(Eq 12)}$$

where y is the SN ratio of the observed value from the experiment and n equals the total number of observed values.

3.3.3 Total Sum of Squares (TSS).

$$\text{TSS} = \sum_{j=1}^{n} y_j^2 - \text{CF} \quad \text{(Eq 13)}$$

3.3.4 Sum of Square (SS).

$$\text{SS} = \frac{\sum_{i=1}^{n/m}\left(\sum_{j=1}^{m} y_{ij}\right)^2}{m} - \text{CF}, \quad \text{(Eq 14)}$$

where y_{ij} is the number j observed value of the i level and m is the number of observed values in each level.

3.3.5 Error Sum of Square (SSE).

$$\text{SSE} = \text{TSS} - \sum_{k=1}^{p} \text{SS}_p, \quad \text{(Eq 15)}$$

where p is the number of factors.

3.3.6 Mean Square & Error Mean Square (MS & MSE).

$$\text{MS} = \frac{\text{SS}}{\text{DF}} \quad \text{(Eq 16)}$$

$$\text{MSE} = \frac{\text{SSE}}{\text{DFE}} \quad \text{(Eq 17)}$$

3.3.7 F-Ratio. The relationship between the factor effect and the error deviation is represented using the F-ratio. The greater the F-ratio, the more profound the effect that the respective factor has on the system. Therefore, the F-ratio can be used to arrange the factors into order of importance. When the F-ratio is less than 1, the effect of that factor is considered to be small. When the F-ratio is greater than 2, the effect of that factor is no longer considered to be small, and an F-ratio greater than 4 means that the corresponding factor has a profound effect on the system. F-ratio is defined as the mean square of the factor divided by mean square of the pooled error.

$$F = \frac{\text{MS}}{\text{MSE}} \quad \text{(Eq 18)}$$

3.3.8 Pure Sum of Square.

$$\text{SS}' = \text{SS} - \text{DF} \times \text{MSE} \quad \text{(Eq 19)}$$

3.3.9 Percentage of Contribution.

$$\rho = \frac{\text{SS}'}{\text{TSS}} \times 100\% \quad \text{(Eq 20)}$$

3.4 Confidence Interval

Through ANOVA, significance analysis, and contribution analysis, a standard method is obtained for the rating of control factors chosen by light-guide plate processing parameters. Therefore, using the response table and response graph, the factor combinations which will improve the experiment results may be predicted in advance, and then a verification experiment is carried out to observe whether the analysis of the results from this experiment are within an acceptable CI with the predicted results. Later the rationality of the mathematical model can be proved established by the data obtained through the experiment of the orthogonal array. At the same time, from the obtained optimum factor level setting value, the addition model is able to be applied to forecast the SN ratio under the optimum processing parameter combination; its calculation formula is as follows:

$$\hat{S}N = \overline{T} + \sum_{i=1}^{n}(F_i - \overline{T}) \quad \text{(Eq 21)}$$

$\overline{T}$ is the average of all the SN ratios and F_i is the SN ratio of significant factor level values.

To effectively evaluate the various observed values, their CI must be calculated. Its calculation is as shown below:

3.4.1 The CI of the Theoretically Predicted Value.

$$\mathrm{CI}_1 = \sqrt{F_{\alpha;1,\nu_2} \times \mathrm{MSE} \times \frac{1}{n_{\mathrm{eff}}}} \quad \text{(Eq 22)}$$

$F_{\alpha;1,\upsilon_2}$ is the F-ratio of significance level α; α is the significance level, the confidence level is $1-\alpha$; ν_2 is the DF of the mean square of the pooled error; MSE is the mean square of the pooled error; n_{eff} is the effective observed value.

$$n_{\mathrm{eff}} = \frac{T_{\mathrm{n}}}{1+T_{\mathrm{s}}}, \quad \text{(Eq 23)}$$

where T_{n} is total number of experiments and T_{s} is the sum of the DF used to estimate the factor of the average value.

3.4.2 The CI of the Calculated Experiment Value.

$$\mathrm{CI}_2 = \sqrt{F_{\alpha;1,\nu_2} \times \mathrm{MSE} \times \left(\frac{1}{n_{\mathrm{eff}}}+\frac{1}{r}\right)}, \quad \text{(Eq 24)}$$

where r is the number of verification experiments.

Finally, a CI of 95% is used to verify whether the predicted average value is acceptable or not, the verification equation is

$$\hat{\mathrm{S}}\mathrm{N} - \mathrm{CI} \le \mu \le \hat{\mathrm{S}}\mathrm{N} + \mathrm{CI} \quad \text{(Eq 25)}$$

4. Results and Discussion

First, the control factors which affect the quality characteristics and their levels have to be obtained. Through related studies and literatures of the past, characteristics of injection molding materials, and discussion with injection molding engineers with profound experience in the field, a feasible combination of processing parameters and their levels were found. Then the experiments were actually tried out, and the other levels that could result in deviations in the quality of light-guide plates were tried to find, thereby identifying a suitable working range. Finally, for the light-guide plate injection molding processing parameters, the factors that were actually controllable by the injection-molding machine were chosen, which are cooling time, mold temperature, melt temperature, injection speed, injection pressure, packing pressure, packing switching, and packing time. The light-guide plate V-cut depth and angle were set as quality characteristics, whose target values are 2.887 μm and 120°, respectively. Since the difference between the quality characteristics of the light-guide plate and the target values was required as small as possible, the smaller-the-better was selected shown in Eq 1. The control factors chosen for the experiment and their levels are shown in Table 2. In Table 2, only one of eight control factors has 2-level, i.e., control factor A in this study. For this reason, the Level 3 column of response table has no symbol, a blank space.

When the initial setting condition was achieved, the V-cut light-guide plates molded had agreement after 20 injection molding. For evaluating the variance of V-cut light-guide plates molded, the surface profile measuring system was employed to measure next 10 molded products. As shown in Fig. 10, three dotted lines were followed by using surface-profile measuring system to measure the angle and depth of molded light-guide plates in order to ensure the agreement of the molded light-guide plates. This could more understand the whole quality and variance of molded light-guide plates, and avoid shrinkage, warpage, short and cracking affecting the agreement of V-cut depth and angle. In addition, when the processing parameters changed and reached setting condition, the injection machine could allow the variance of V-cut light-guide plates molded to settle between parameter changes after three injection molding.

Table 2 Eight control factors and their levels

Control factors	Levels 1	2	3
A. Cooling time, s	15	30	
B. Mold temperature, °C	75	80	85
C. Melt temperature, °C	250	260	270
D. Injection speed, mm/s	165	180	195
E. Injection pressure, MPa	220	240	260
F. Packing pressure, MPa	90	100	110
G. Packing switching, mm	5	10	15
H. Packing time, s	1	2	3

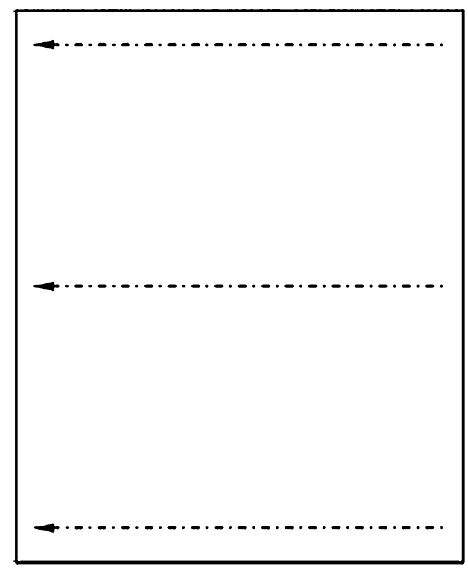

Fig. 10 The measuring method for checking the variance of molded V-cut microstructure

Then the control factor and their levels were substituted from Table 2 into the $L_{18}(2^1 \times 3^7)$ orthogonal array to serve as the plan and procedures for carrying out the experiment. Afterward the 18 experiments were proceeded with in accordance with the experiment plan. Each experiment was repeated three times. The absolute value of the difference between the target values and the actual data collected from the experiment, 54 pieces of data from the experiment in total, then the SN ratio for each experiment was calculated according to the data collected from the experiments, the results are shown in Table 3.

The ANVOA table was calculated out of the SN ratios in Table 3, as shown in Table 4 and 5. From the ANOVA table that with regard to the V-cut depth, control factors A, C, D, and E have a smaller effect and are therefore categorized as pooled errors; on the other hand, control factors B, F, G, and H all have an F-ratio greater than 4, meaning that the effects of these

Table 3 The orthogonal array with the averages and SN ratios of Depth/Angle

Experiment no.	A	B	C	D	E	F	G	H	Mean of Depth (μm)	Mean of Angle (degree)	SN ratio of Depth, dB	SN ratio of Angle, dB
1	15	75	250	165	220	90	5	1	1.7304	138.2667	−1.2642	−25.249
2	15	75	260	180	240	100	10	2	2.2867	129.5333	4.4274	−19.595
3	15	75	270	195	260	110	15	3	2.1826	133.5333	2.9626	−22.657
4	15	80	250	165	240	100	15	3	2.2292	135.2667	3.6345	−23.680
5	15	80	260	180	260	110	5	1	2.1144	135.5000	2.2403	−23.813
6	15	80	270	195	220	90	10	2	2.3142	133.2667	4.8317	−22.456
7	15	85	250	180	220	110	10	3	2.2692	135.4667	4.1817	−23.788
8	15	85	260	195	240	90	15	1	2.0623	134.4667	1.6743	−23.213
9	15	85	270	165	260	100	5	2	2.6599	128.4667	12.8749	−18.608
10	30	75	250	195	260	100	10	1	1.7122	138.9667	−1.3997	−25.562
11	30	75	260	165	220	110	15	2	2.3744	128.7667	5.7975	−18.870
12	30	75	270	180	240	90	5	3	2.1937	132.9000	3.1804	−22.229
13	30	80	250	180	260	90	15	2	2.2873	128.9667	4.4402	−19.069
14	30	80	260	195	220	100	5	3	2.3320	135.7000	5.1019	−23.919
15	30	80	270	165	240	110	10	1	2.0347	136.2000	1.3876	−24.192
16	30	85	250	190	240	110	5	2	2.6880	126.9333	14.0177	−16.843
17	30	85	260	165	260	90	10	3	2.3671	130.6667	5.6226	−20.570
18	30	85	270	180	220	100	15	1	2.1813	134.5667	3.0267	−23.274

Table 4 Analysis of variance table for V-cut depth

Source	DF	SS	MS	*F*-ratio	SS′	ρ
A	1	1.75 (a)	···	···	···	···
B	2	67.80	33.90	23.25	64.88	24.85
C	2	1.93 (a)	···	···	···	···
D	2	4.23 (a)	···	···	···	···
E	2	4.02 (a)	···	···	···	···
F	2	13.29	6.65	4.56	10.38	3.97
G	2	28.45	14.23	9.76	25.54	9.78
H	2	138.41	69.20	47.46	135.49	51.90
Error	2	1.19	···	···	···	···
(Pooled error)	9	13.12	1.46		24.79	9.49
Total	17	261.08			261.08	100

Note: (a) The pool-up terms

Table 5 Analysis of variance table for V-cut angle

Source	DF	SS	MS	*F*-ratio	SS′	ρ
A	1	4.04	4.04	4.39	2.20	2.02
B	2	10.44	5.22	5.67	8.60	7.89
C	2	1.67 (a)	···	···	···	···
D	2	1.16 (a)	···	···	···	···
E	2	6.34	3.17	3.44	4.50	4.13
F	2	1.69 (a)	···	···	···	···
G	2	3.30 (a)	···	···	···	···
H	2	78.96	39.48	42.86	77.11	70.75
Error	2	1.39	···	···	···	···
(Pooled error)	10	9.21	0.92		16.58	15.21
Total	17	108.99			108.99	100

Note: (a) The pool-up terms

factors are all profound; therefore these factors are all significant factors. The significant factors for the V-cut angle are factors A, B, E, and H.

In addition, GRA was employed to perform optimum processing parameter combination analysis. The target values for V-cut depth and angle were used as the reference sequence, which was X_0 = (2.887, 120). The deviation sequence for the reference sequence and the sequences in the orthogonal array, the grey relational coefficients, and grey relational grade calculation results are shown in Table 6. Next the GRA response table and response graph could be obtained using main effect analysis, as shown in Table 7 and Fig. 11. From the response table and response graph, the optimum processing parameter combination for light-guide plate injection molding was determined, which is A2, B3, C3, D1, E2, F3, G1, and H2. In other words, the cooling time of 30 s, mold temperature of 85 °C, melt temperature of 270 °C, injection speed of 165 mm/s, injection pressure of 240 MPa, packing pressure of 110 MPa, packing switching of 5 mm, and the packing time of 2 s.

Table 6 The deviation sequences, grey relational coefficients and grades

No.	$\Delta_{0,i}(1)$	$\Delta_{0,i}(2)$	$\gamma_{0,i}(1)$	$\gamma_{0,i}(2)$	$\gamma_{0,i}$	Rank
1	0	38.339	1	0.34055	0.67027	17
2	0	15.081	1	0.56763	0.78381	6
3	0	19.615	1	0.50233	0.75116	12
4	0	19.114	1	0.5088	0.7544	11
5	0	22.519	1	0.46786	0.73393	14
6	0	16.021	1	0.55273	0.77637	7
7	0	18.132	1	0.52196	0.76098	9
8	0	23.637	1	0.45582	0.72791	15
9	0	6.7319	1	0.74626	0.87313	2
10	0	39.597	1	0.33333	0.66667	18
11	0	12.666	1	0.60986	0.80493	3
12	0	19.017	1	0.51007	0.75503	10
13	0	14.818	1	0.57194	0.78597	5
14	0	16.625	1	0.54357	0.77178	8
15	0	25.373	1	0.4383	0.71915	16
16	0	5.6566	1	0.77778	0.88889	1
17	0	13.636	1	0.59217	0.79608	4
18	0	20.125	1	0.49591	0.74795	13

After the optimum light-guide plate processing parameter combination was obtained through GRA, the verification experiments were conducted. First, the theoretical predicted values could be figured out through the significant factors in the ANOVA table. According to Eq 21, the predicted values for the V-cut depth and angle were 12.9646 and −17.2646 dB, respectively; according to Eq 22, the expected average value

Table 7 The response table for the GRA

	A	B	C	D	E	F	G	H
Level 1	0.7591	0.7386	0.7545	0.7697	0.7554	0.7519	0.7822	0.7110
Level 2	0.7707	0.7569	0.7697	0.7613	0.7715	0.7663	0.7505	0.8189
Level 3		0.7992	0.7705	0.7638	0.7678	0.7765	0.7621	0.7649
Difference	0.0116	0.0605	0.0159	0.0084	0.0162	0.0246	0.0317	0.1079
Rank	7	2	6	8	5	4	3	1

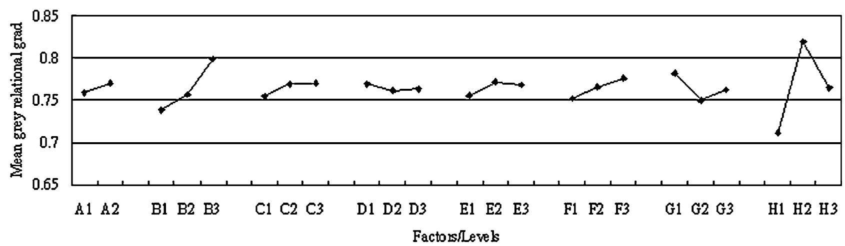

Fig. 11 The response graph for the GRA

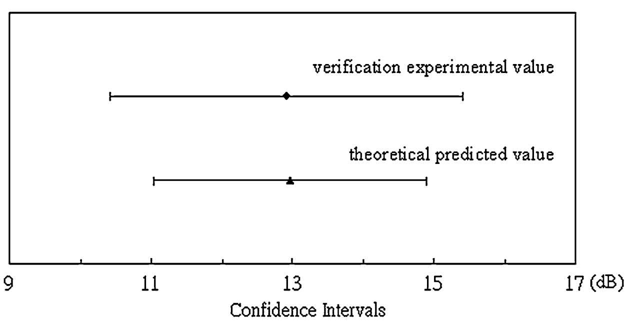

Fig. 12 Diagram for the CI of the V-cut depth verification experimental value and theoretical predicted value

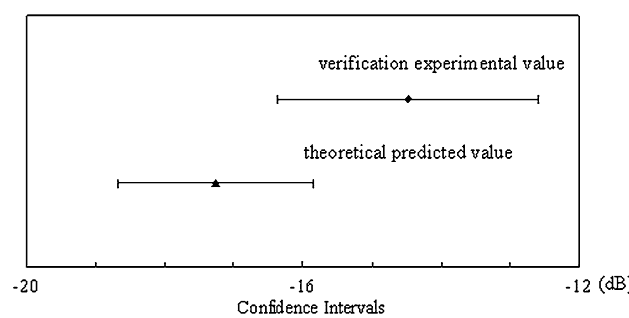

Fig. 13 Diagram for the CI of the V-cut angle verification experimental value and theoretical predicted value

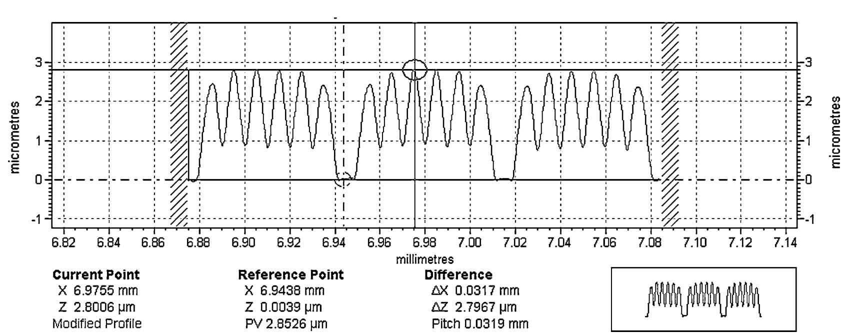

Fig. 14 The V-cut depth of the optimum processing parameter combination

of the 95% CI of the V-cut depth and angle were 1.9333 and 1.4240 dB, respectively. After three verification experiments, the experimental average value of the V-cut depth and angle were 12.9158 and −14.4736 dB, respectively. According to Eq 24, the expected average value of the V-cut depth and angle of a 95% CI were 2.4960 and 1.8840 dB, respectively. The diagram for the CI of the V-cut depth and angle verification experiment values and theoretical predicted values are shown in Fig. 12 and 13, respectively. From the diagrams, the CI from the verification experiment and the theoretical predictions did indeed coincide; therefore the results from our experiment are indeed reliable had been proven. The V-cut depth and angle of the optimum processing parameter combination measured by the surface profile measuring system are shown in Fig. 14 and 15, respectively. Table 8 shows the percentage error between the verification experiment values and the target values. The average error for depth and angle are 2.6879% and 4.3889%, respectively.

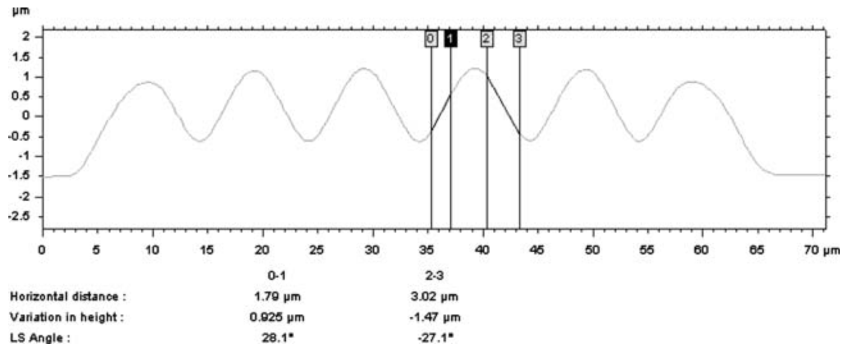

Fig. 15 The V-cut angle of the optimum processing parameter combination

Table 8 The percentage errors for the verification experiment values and the target values

	Verification experiment values		Target values		Error (%)	
Confirmation experiment No.	**Depth, µm**	**Angle, degree**	**Depth, µm**	**Angle, degree**	**Depth, µm**	**Angle, degree**
1	2.8297	124.8	2.887	120	2.0471	4
2	2.7967	125	2.887	120	3.1278	4.1667
3	2.8036	126	2.887	120	2.8889	5

5. Conclusions

The GRA combined with the Taguchi method was applied to find the optimum level for a light-guide plate processing parameter in the least amount of experiments possible. From the response table and response graph obtained from GRA, the optimum processing parameter combination for light-guide plate injection molding was concluded as: the cooling time of 30 s, mold temperature of 85 °C, melt temperature of 270 °C, injection speed of 165 mm/s, injection pressure of 240 MPa, packing pressure of 110 MPa, packing switching of 5 mm, and the packing time of 2 s. From Table 4 the factors that more significantly affected the V-cut depth are mold temperature, packing pressure, packing switching, and packing time. From Table 5 the factors that more significantly affected the V-cut angle are cooling time, mold temperature, injection pressure, and packing time. After carrying out three verification experiments, the diagrams for the CI for the verification experimental values and theoretical predicted value of the V-cut depth and angle were obtained, which are shown in Fig. 12 and 13, respectively. Their conclusion proved that the results of this experiment possess reproducibility, showing that the chosen significant factors were indeed suitable, and at the same time proved that this experiment is indeed reliable. In addition, Table 8 compares the percentage errors for the verification experiment values and the target values, the average error for depth and angle were 2.6879% and 4.3889%, respectively, and that the optimum processing parameter combination for light-guide injection molding could indeed be obtained was verified using GRA and the Taguchi method. In addition, GRA combined with the Taguchi method was also suitable for the optimization of processing parameters for other types of processes, and could have a substantial effect on increasing the efficiency of that process.

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