Determining the injection molding process window based on form accuracy of lenses using response surface methodology

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Abstract The purpose of this study is to establish a process window for injection molding processes for the optimal form accuracy of spherical lenses. First, the significant factors influencing lens form accuracy are identified by Taguchi parameter design. These key factors are used to perform full factorial experiments and to establish the response surface model. Next, the concave response surface of form accuracy obtained by Central Composite Design is used to obtain the injection molding process window for a given spherical lens form accuracy. As a result, the injection molding process window is elliptical, with the best form accuracy being 0.3758 μm at the elliptical center when the mold temperature is 85 °C, the cooling time is 9.6 s, and the packing time is 1.9 s. The average error is 7.92 % based on experimental verifications for three mold temperatures. In addition, a lens with a form accuracy of 0.5 μm is taken as an example to validate the injection molding process window. The results show that the average error between the experimental data and the prediction values is 10.58 %. Therefore, the proposed method for constructing a process window is reasonably accurate.

Keywords Injection molding · Optical lens · Taguchi method · Response surface methodology · Process window

1 Introduction

The plastic injection molding process is characterized by high efficiency, high productivity, low cost, automation, and applicability for designing complex products, and is the most commonly used technique for the production of spherical plastic lenses. The injection molding process consists of three main stages, filling, packing/holding, and cooling. The polymer properties, mold structure, and injection molding parameters must be considered at each stage. The process parameters are highly correlated with the quality of molded products [1–3], as poor process parameter settings will result in multiple defects in the molded parts, such as warpages, shrinkages, voids, and sink marks. Defects in molded plastic lenses will change the surface profile of the lenses, influencing their dimensional accuracy and optical performances [4–7].

Plastic injection molding has many related process parameters. To save experimental cost and time, the Design of Experiment (DOE) [8–10] is widely used for screening experiments, especially the Taguchi Parameter Design, which is a high efficiency parameter screening procedure that has been extensively used in different manufacturing process studies, such as injection molding [11–16], machining [17–19], and plastic forming [20, 21].

Based on many researches listed above, the quality of injection molded parts strongly depends on the product shapes, mold designs, plastic properties, and molding conditions. In order to obtain better quality injection molded lenses, the control of injection molding parameters is of particular importance in addition to the fabrication accuracy of the mold. However, due to the complexity of the thermal viscoelastic behavior of melt in the cavity and the nonlinear nature of the system, it is difficult to predict the molding quality. Many scholars have used multiple operating conditions to determine the optimal parameters for the best quality, a method called forward modeling [11–21]. On the other hand, the formula for the inverse modeling, that is, compute the process parameters from given quality characteristics of the products, is difficult to find analytically. Therefore, many researches have used various approaches to determine processing parameters of
injection molding [22, 23]. This study uses inverse modeling to determine the appropriate process window for the specified products’ quality requirements in order to obtain the lowest cost operating conditions at which the quality requirements are matched. This study therefore uses the form accuracy of spherical lenses as a quality characteristic, and uses the Taguchi method to identify the optimal combination of process significant factors. The response surface model based on significant factors influencing the lens form accuracy is established using response surface methodology. Finally, the process window is constructed using curve fitting according to specified quality requirements.

2 Response surface methodology

Response surface methodology (RSM) is a model-building research method that incorporates statistics [24–27]. It uses appropriate polynomial models to approximate the relationship between the response variable of a problem and several independent variables. The model parameters can use DOE to collect data, and the least square method is often used for fitting the surface model. When the relationship between the response variables of engineering problems and several independent variables is too complex or unknown, RSM is usually used [28–35]. Therefore, the ultimate purpose of RSM is to determine the optimum operating parameters of a system, or the range of the factor space, so as to match the operating requirements.

This study uses the significant factors obtained from the Taguchi experiment to establish the response surface model of quality characteristics. In order to draw the response surface model, the response surface model of three process factors is used. The model uses the following quadratic polynomial equation with interaction:

$$y = \beta_0 + \sum_i \beta_i x_i + \sum_{i<j} \beta_{ij} x_i x_j + \sum_{i,j,k} \beta_{ijk} x_i x_j x_k + \varepsilon$$

$$= \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 AB + \beta_5 AC + \beta_6 BC + \beta_7 ABC$$

$$+ \beta_8 A^2 + \beta_9 B^2 + \beta_{10} C^2 + \beta_{11} A^2 B + \beta_{12} A^2 C + \beta_{13} AB^2$$

$$+ \beta_{14} AC^2 + \beta_{15} B^2 C + \beta_{16} BC^2 + \varepsilon$$

(1)

where $y$ is the response variable; $\beta$ is the undetermined coefficient; $x$, $A$, $B$ and $C$ are independent variables; and $\varepsilon$ is the model error.

In the response surface model, in order to express the fitness of the model for experimental data, the coefficient of determination ($R^2$) is often used to determine the accuracy of the model. The larger the $R^2$ is, the higher the fitness will be, i.e., the closer the model prediction value will be to the experimental value. $R^2$ is defined [31] as:

$$R^2 = \frac{\text{Regression sum of squares (SSR)}}{\text{Total sum of squares (SST)}}$$

$$= 1 - \frac{\text{Error sum of squares (SSE)}}{\text{Total sum of squares (SST)}}$$

(2)