Gate design optimization in the injection molding of the optical lens

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Injection molding processing is used widely in the manufacturing of precision optical lens, and the gate design is an important factor to dominate the optical lens performances. In this paper, the mold flow technology combined with the Taguchi method used to analyze the geometrical parameters optimization about the gate design on the injection molding of the optical lens. To design the optimum gate parameters, the Taguchi method (including the orthogonal array $L_9 3^4$, the Signal-to-Noise ratio S/N, and the Analysis of Means-ANOM) is employed to analyze the affect factors of the gate shape and to determine the optimum gate geometrical parameters. The analyzed model including the gate and lens are used to process the injection molding simulation of the Taguchi method, and then to analyze and calculate the average residual stress in a fixed plane of the lens. The major objective is to elevate the lens performance by means of reducing average residual stress. The results show the average residual stress is decreasing with S/N increasing, and the smaller residual stress distribution lead to the lens performance is elevated. The optimal combination of control factor (level) is A(3), B(3), C(3), and D(2), and the combination parameters of the optimum process with S/N=48.438dB can reduce the average residual stress to 0.002753MPa. The control factors with their importance about the improving average residual stress in the injection molding processing are (A)- gate thickness, (C)- gate inlet width, (B)- gate length, and (D)- gate outlet width.

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1. Introduction

Injection molding is an important polymer processing technology for providing short product cycles, high-quality part surface, low costs, and light weight. Consequently, the quality control of the injection molding product is a priority for the today plastic industry. However, the injection molding processing is a quite complex, non-steady state, multi-variable processing with non-linear, time-dependent materials [1, 2]. In the filling time, the molten melt is passing through the gate from runner system into mold cavity. Hence, gates are very important units in the injection molding processing. The gates in the injection molding can be divided into the sprue gate, common edge gate, lapped edge gate, notched edge gate, fan gate, film gate, flash gate, ring gate, tunnel gate, and diaphragm gate. Some typical gates are shown in the Fig. 1. Gate designs (including size, shape, and position) are critical to the successful injection molding of plastic parts [3]. The gate plays a linking role between the runner system and mold cavity, and can significantly affect the quality of the molded parts. Residual stresses influence the properties of injection molding products. An optical lens needs precisely controlled residual stress to realize its optical design performance [4, 5]. In general, the injection molding processing is not ideal for lens since good optical performance is very difficult to be achieved to free shrinkage and stress induced distortion [6]. Residual stresses introduce birefringence which is an asymmetry of the refraction index can make a plastic lens unable to focus properly. Hence, the residual stress will lead to the molded lens form deterioration of optical performance. To improve the optical performance of molded lens, and the best method is to reduce the residual stress in the lens. Hence, the authors try to using the Taguchi method combined with the mold flow analysis technology to process the gate optimization analysis of the injection molding. Taguchi method is a statistical method developed by Genichi Taguchi to improve the quality of manufactured goods, and more recently also applied to, engineering, biotechnology, marketing and advertising [7-9]. Moreover, a design-of-experiment (DOE) approach can provide both qualitative and quantitative process knowledge via well-planned balanced experiments and efficient acquisition and analysis of subsequent experimental data. A Taguchi method of $L_9(3^4)$ is generated in this paper to find variability in the lens performance of the injection molding considering residual stress effects.

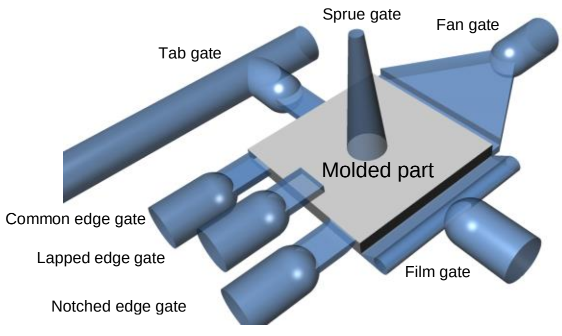

Fig. 1. Gate types in the injection molding.

2. Residual stress in the molded lens

2.1. Residual stress, refractive index, and isochromatic fringe order

Residual stresses are important criteria for evaluating molded optical lenses, and they exist inside plastic lenses can cause refractive index variation, undesired light-path deviation, as well as intensity change that can result in image quality distortion. In general, the residual stress can be analyzed by using birefringence is based on the photo-elastic effect. The test lens is impinged with a polarized light beam. If the principal indices of a lens coincide with the principal stresses at a point in the lens, the following equations can be used to describe the relationship between the principal indices and the principal stresses [10, 11].

$$n_1 - n_2 = C(\sigma_1 - \sigma_2), \tag{1}$$

$$n_2 - n_3 = C(\sigma_2 - \sigma_3), \tag{2}$$

$$n_3 - n_1 = C(\sigma_3 - \sigma_1), \tag{3}$$

where C is stress-optic constant, n_i are the refractive indices along the principal axis, and σ_i are the principal stresses. When polarized light passes through the stressed lens, the light separates into two wave-fronts, each oriented parallel to a direction of the principal stresses σ_1, σ_2. These are transmitted with different velocities and one mergence the relative retardation is:

$$\delta = (n_1 - n_2)d = Cd(\sigma_1 - \sigma_2), \tag{4}$$

$$N = \delta/\lambda = Cd(\sigma_1 - \sigma_2)/\lambda, \tag{5}$$

where d is the thickness of the lens, and λ is the wave length of the light. Equations (4) and (5) show the difference in the principal stresses at any point in a photo-elastic sample, which is directly proportional to the isochromatic fringe order N. These equations also express the stress-optical law, which is also known as Brewster's law. Hence, the relationships among residual stress, refractive index, and isochromatic fringe order can be connected by Eqs. (1, 4, 5).

2.2. Residual stress and gate design

Generally, the gate should be designed to allow for easy removal from the part, and the gate length should be short as possible to reduce pressure drop. An important issue must be mentioned, the injection parts are possessed with the pressure gradient across themselves during molding filling and packing. The highest pressure is near the gate compared to away from the gate. High pressure regions will be packed out better than the low pressure regions, and it will cause the high and low pressure regions to shrink at a different rate. The results will be able to be expected the gate area of the part will shrink less than far regions of the molded part. Different shrinkage rate will result in conflicting strains, and the residual stress will be developed in an injection molding part. The complex shrinkage behavior of the plastic part should be the most dominant problem associated with the good parts of the injection molding.

3. Optimization using taguchi method

3.1. Taguchi experiments using mold flow analysis

In the Taguchi analysis, the low average residual stress is considered as the objective condition of the gate geometrical parameters optimization. ***Moldex3D*** Software is used as an important tool in executing the Taguchi experimentations of the injection molding simulation. Results combined with the molding conditions can be useful in optimizing process parameters. Fig. 2 shows the sample mold and mesh for the manufacturing of the optical lens is used to process the injection molding simulation experiment.

Table 1. Material data of PMMA (ZYLAR330, INEOS).

Category	Data	[unit]
ρ: density	1.05	[g/cm^3]
μ: viscosity (T: 300-320 ºC; $\dot{\gamma}$: 10-10^5)	51-3.2x10^4	[g/(cm·sec)]
ν: Poisson ratio	0.4	[-]
E: Young's modulus	2.3x10^{10}	[dyne/cm^2]
G: torsion modulus	1.5x10^6	[dyne/cm^2]
α: coefficient of thermal expansion	7x10^{-5}	[1/K]
k: coefficient of heat conduction	2.1x10^4	[erg/(sec·cm·ºC)]
C_p: specific heat	2.3x10^7	[erg/(g·ºC)]
C_v: specific volume(T: 10-300 ºC; P: 0-200MPa)	0.912-1.126	[cm^3/g]
Suggested mold temp.	20-60	[ºC]
Suggested melt temp.	200-240	[ºC]

Table 2. Geometrical parameters control factors for three levels of Taguchi method.

Factor	Description (unit)	Level 1	Level 2	Level 3
A	Gate thickness (mm)	2.6	4.6	6.6
B	Gate length (mm)	4	6	8
C	Gate inlet width (mm)	4	6	8
D	Gate outlet width (mm)	13	15	17

PMMA (ZYLAR330, INEOS) is selected as the material of the injection molding simulation experiments. The material properties are listed in Table 1. Fig. 3 demonstrates the steps of Taguchi parameter design [7-9].

3.2. Design-of-experiment and signal to noise ratio (S/N)

This analysis chooses the smaller-the-better quality characteristic to calculate the average residual stress through the orthogonal array of $L_9(3^4)$ optimal levels of process parameters. From the original design (level 2), three levels of the four factors are chosen as shown in Table 2, and the chosen factors are described as following: (A) Gate thickness; (B) Gate length; (C) Gate inlet width; (D) Gate outlet width. Taguchi technique utilizes the signal noise ratio (S/N) approach to obtain the quality characteristics from the simulation experiments. The S/N ratio is used to convert the experimental results into a value for evaluation characteristic in the optimum parameter analysis [10]. The smaller-the-better equation of the S/N ratio is described as following.

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

where y_i is the residual stress in each measured points; n is the number of the measured points in a trial. The numerical tests scheduled in the experimental plan of the Taguchi method (see Table 3) are simulated by using the injection molding software - ***Moldex 3D***.

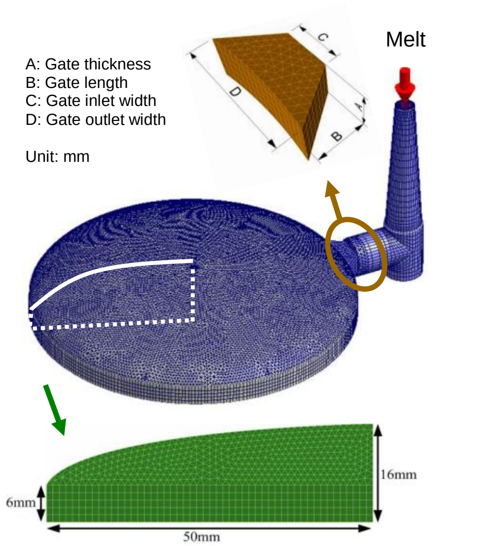

Fig. 2. Geometrical parameters and finite element mesh in gate design.

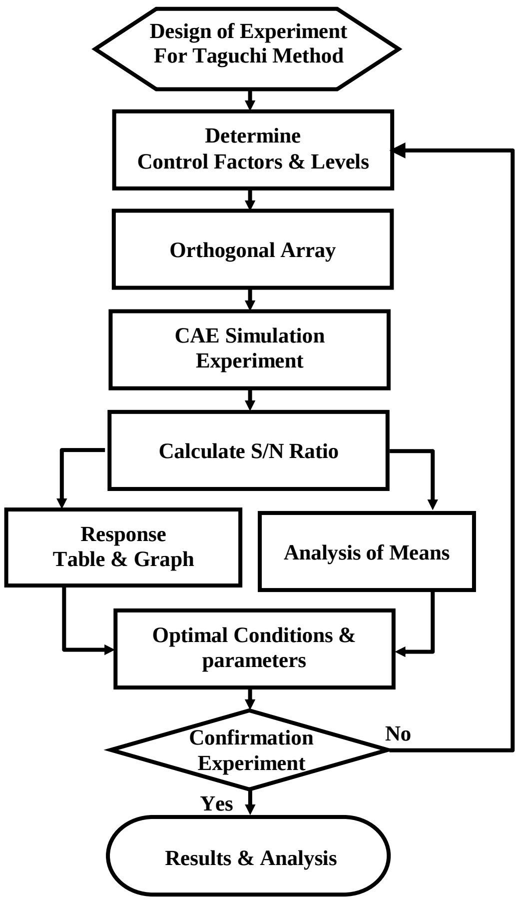

Fig. 3. The flow chart of the Taguchi method.

3.3. Analysis of means and confirmation experiments

Analysis of means (ANOM) is a statistical technique used in illustrating important variations among groups of experimental data. Employed commonly in quality control, ANOM methodology compares the mean of each group to the overall process mean to detect statistically significant differences. In this analysis, the gate geometrical parameter is a key issue to effect the average residual stress.

$$M=\frac{1}{k}\sum_{j=1}^{k}(S/N)_j\,, \tag{7}$$

where M is the average of the S/N ratio values in the all experiments of the specified level; k is the total number of the experiments in the specified level. To obtain the optimal processing parameters and improve the residual stress in the injection molding, the analysis of means (ANOM) should be used to find the residual distribution in the runner by a specified processing parameter. The purpose of the analysis was to find which parameters significantly affected the quality characteristic of the optical lens.

To verify the results of the Taguchi experiments, confirmation experiments are executed at the optimum combination of factors and levels. The predicted value for S/N ratio at the optimum combination of factors and levels can be expressed as following [12].

$$(S/N)_{\text{Pre}}=\bar{\eta}+[\bar{A}-\bar{\eta}]+[\bar{B}-\bar{\eta}]+[\bar{C}-\bar{\eta}]+[\bar{D}-\bar{\eta}]\,, \tag{8}$$

where $(S/N)_{\text{Pre}}$ is the predicted value of the S/N ratio; $\bar{\eta}$ is the average of the S/N ratio in the experiments; $\bar{A}$, $\bar{B}$, $\bar{C}$, and $\bar{D}$ are the optimum combination of factors and levels.

Table 3. Experimental plan using L9 Orthogonal array (Gray Area) with the corresponding results for average residual stress and S/N ratio.

Exp.	Gate thickness **(mm)**	Gate length **(mm)**	Gate inlet width **(mm)**	Gate outlet width **(mm)**	Average residual stress. **(MPa)**	**S (MPa)**	**S/N(dB)**
1	2.6	4	4	13	0.032633	0.032622	26.718
2	2.6	6	6	15	0.011512	0.011505	35.769
3	2.6	8	8	17	0.006163	0.006156	41.199
4	4.6	4	6	17	0.008579	0.008575	38.323
5	4.6	6	8	13	0.00462	0.004617	43.7
6	4.6	8	4	15	0.006599	0.006594	40.603
7	6.6	4	8	15	0.003519	0.003516	46.064
8	6.6	6	4	17	0.005488	0.005484	42.204
9	6.6	8	6	13	0.003375	0.003371	46.429
				Ave.	0.009	0.009	40.112

Table 4. S/N ratio response.

	A	B	C	D
Level 1	34.56	37.04	36.51	38.95
Level 2	40.88	40.56	40.17	40.81
Level 3	44.90	42.74	43.65	40.58
$E^{1\text{-}2}$	-6.32	-3.52	-3.66	-1.86
$E^{2\text{-}3}$	-4.02	-2.18	-3.48	0.23
Range	10.34	5.71	7.15	1.86
Rank	1	3	2	4

Table 5. Comparisons of predictive response results and confirmation experiments.

	Ave.	S	Exp. S/N	Pre. S/N
Original	0.00552	0.005516	42.154	40.938
Optimal	0.002753	0.00275	48.199	48.438
		Improvement	6.045	7.5

4. Results and discussions

4.1. The S/N response graph in the Taguchi analysis

The simulation results obtained in this study yield a useful understanding of the factors responsible for the average residual stress which should be applied to minimize this effect. Table 3 indicates the average residual stress and S/N ratio for each of the nine experiments configured in the Orthogonal Array. S/N ratio response results (see Table 4) list the S/N responses of the average residual stress in every level (Level 1-3) of the four gate geometrical parameters (A, B, C, and D). In this study, we seek to minimize the average residual stress to attain the good lens optical performance. Fig. 4 shows the response graph for the average residual stress. As shown in Eqs. (6) and (7), the greater is the S/N ratio, the smaller is the variance of the average residual stress around the desired (the smaller-the -better) value.

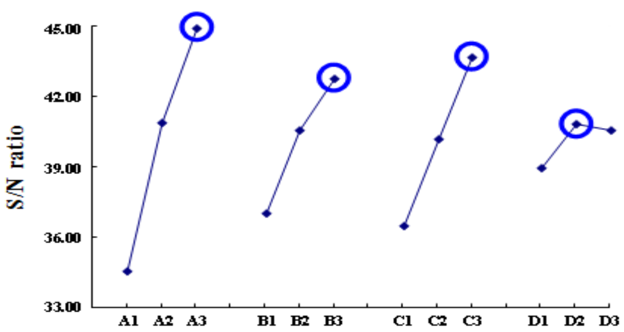

Fig. 4. S/N ratio vs. average residual stress response curves.

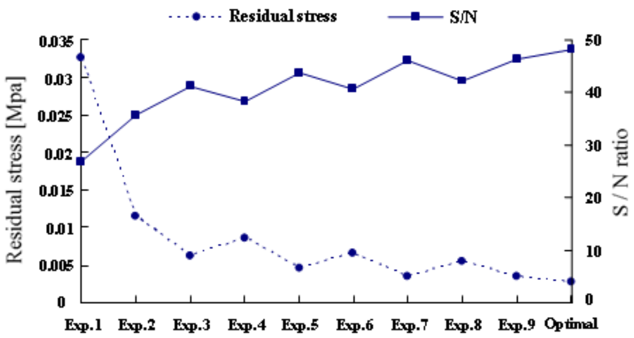

Fig. 5. S/N ratio and average residual stress in the different experiments.

4.2. Confirmation experiments

Fig. 4 shows the optimal combination of control factor (levels) is A(3), B(3), C(3), and D(2)(See the circles in the Fig. 4). The results of the confirmation experiments are compared with the predicted value to verify the validity of the Taguchi experiments. The average of S/N ratio is 40.112dB, by the Taguchi $L_9(3^4)$ experiments (See Table 3). In the Table 5, it shows the S/N ratio is equal to 48.199dB under the optimal conditions, and has an increment 6.045dB compared with the original (S/N=42.154dB) of the test experiments. The calculated values for the predicted S/N ratio are 40.938dB and 48.438dB (the increment =7.5dB) at the original and optimum designs, respectively. Above statistics shows there are very good consistency between the simulation experimental values and theoretical predicted values. The results show the optimal geometrical parameters in the injection molding simulation can effectively reduce the average residual stress. The average residual stress can be improved, and the average residual stress in the optimal geometrical conditions can be reduced to 0.002753MPa (See Fig. 5).

4.3. The Influence factors (gate geometrical parameters)

Basically, the key features of the injection molding gate are to allow for easy to automatically separate the part and the runner system and to allow for filling and packing of the part. For an advanced function is to reduce the residual stress, and the significant result in reducing residual stress among the four parameters can be analyzed and presented as gate thickness, gate inlet width, gate length, and gate outlet width in sequence. Hence, it is verified in this analysis that the gate thickness is still a key factor to determine the residual stress.

4.4. Residual stress, refractive index and isochromatic fringe order

In the injection molding, the manufacturing mechanical processing (filling, packing, cooling, and deformation) brings the residual stress of the molded lens. The formation of the residual stress makes the variation of the refractive index, and isochromatic fringe order can be used to evaluate the optical performance of the molded lens. Hence, a uniform distribution of the refractive index will be desired in the lens manufacturer. The residual stress dominates the refractive index, and the uniform refractive index determines the optical performance of the lens. In this study, the gate geometrical parameters are used to be considered as major cause to affect the residual stress, and the four geometrical factors and three size levels in the Taguchi method are successfully used to determine the optimal parameters combination for reducing the residual stress. Hence, the minimization of the average residual stress is used to be related about the uniform refractive index and lower isochromatic fringe order.

5. Conclusions

Gate design optimization of optical lens in the injection molding is successfully analyzes with Taguchi method. This paper has utilized the Taguchi method combined with ANOM method to determine the importance of controlling factors and to obtain the optimal gate geometrical parameters when minimizing the average residual stress in the injection molding simulation. The influence of all factors has been identified and believed can be a key solution in helping mold designers in determining optimum parameters. The major findings and contributions of this paper can be summarized as follows.

- The minimization of the average residual stress in the lens is determined in order of diminishing influence by the following control factors: (1) gate thickness=6.6 mm, (2) gate inlet width=8 mm, (3) gate length=8 mm, and (4) gate outlet width=15 mm.
- The optimal control factor settings are as follows: (1) gate thickness, (2) gate length, (3) gate inlet width, and (4) gate outlet width.
- The optimum parameters obtained has been verified by confirmed simulation experiment, and the average residual stress can achieve to 0.002753MPa.
- The Taguchi method is suitable to be used to analyze the gate geometrical optimization of the lenses in the injection molding.

Acknowledgments

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