ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 21, No. 2. 2015

Dimensional Accuracy Optimization of the Micro-plastic Injection Molding Process Using the Taguchi Design Method

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crossref http://dx.doi.org/10.5755/j01.mm.21.2.5864

Received 08 December 2013; accepted 29 March 2014

Plastic injection molding is an important field in manufacturing industry because there are many plastic products that are produced by injection molding. However, the time and cost required for producing a precision mold are the most troublesome problems that limit the application at the development stage of a new product in precision machinery industry. This study presents an approach of manufacturing a hard mold with microfeatures for micro-plastic injection molding. This study also focuses on Taguchi design method for investigating the effect of injection parameters on the dimensional accuracy of Fresnel lens during plastic injection molding. It was found that the dominant factor affecting the microgroove depth of Fresnel lens is packing pressure. The optimum processing parameters are packing pressure of 80 MPa, melt temperature of 240 °C, mold temperature of 90 °C and injection speed of 50 m/s. The dimensional accuracy of Fresnel lens can be controlled within ±3 µm using the optimum level of process parameters through the confirmation test. The research results of this study have industrial application values because electro-optical industries are able to significantly reduce a new optical element development cycle time.

Keywords: Fresnel lens, plastic injection molding, precision mold, Taguchi design method.

1. INTRODUCTION

Several micro-molding techniques have been developed for fabricating micro-components or micro-devices [1]. The key to the microfabrication in polymeric substrates using micro-injection molding is the development of a precision mold to fabricate plastic part with microstructures. Several fabrication techniques have been proposed for micro-featured mold fabrication, including micro-casting [2], silicon-based micromachining technology [3], lithographie galvanoformung abformung (LIGA) [4], laser micromachining [5], micro-electro discharge machining (µ-EDM) [6, 7], micro machining [8], deep reactive ion etching [9], electrochemical micromachining [10], focused ion beam [11] and wire electrical discharge machining [12]. However, these methods have some disadvantages, such as complex manufacturing processes, high manufacturing cost and long processing time for fabricating a precision mold with microfeatures. Metal mold can be fabricated by micro machining. However, this method is limited by difficulties with machining of complex microstructures. LIGA technology can produce a very durable but an expensive mold because of the complex manufacturing processes. Silicon molds are usually fabricated by silicon-based micromachining followed by wet or dry etching. However, silicon molds have a limited lifespan due to its high brittleness, adhesions and friction during the micro-injection molding processes. Micro-featured mold can be also fabricated by laser micro machining. However, this method is limited by long processing time. To overcome these problems, a low-cost approach was proposed for fabricating micro-featured mold using silicone rubber. Nevertheless, silicone rubber mold belongs to soft mold that can not be employed in the plastic injection molding because rigidity of silicone rubber mold is not enough for micromolding. Thus, developing a hard mold for plastic injection molding using rapid tooling technique is an important issue.

Plastic materials are widely used in 3C products, optical elements, electronic goods, automotive and packaging. It is well known that plastic injection molding is one of the most important polymer manufacturing processes in plastic industry because it can produce complex-geometry plastic parts with good dimensional accuracy under very short cycle time. In this study, a simple and cost-effective approach for fabricating a precision epoxy resin mold using rapid tooling technology was proposed. The Taguchi design method [13 – 19] is an efficient and effective experimental approach that can reduce the experimental trials to determine the optimum level of process parameters. The correlation of the dimensional accuracy with processing parameters of plastic injection moulding is a complicated issue. Thus, the objective of this study is to determine the optimum level of process parameters for improving the dimensional accuracy of Fresnel lens during plastic injection molding using Taguchi design method. The most significant factor that affects the microgroove depth of Fresnel lens was also investigated. Twenty test parts were employed to prove the effectiveness of Taguchi design method after the optimum level of process parameters were determined.

2. EXPERIMENT

Fig. 1 shows the schematic illustration of process flow for fabricating a precision epoxy resin mold. A plastic Fresnel lens with dimensions of 3 cm × 3 cm was selected as a master pattern. The Al 6061 alloy was first machined

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by a precision universal milling machine as backing plate. A room temperature vulcanization (RTV) silicone rubber (KE-1310ST, Shin Etsu) and rubber resin (UES-9030, Axson) were used as mold materials to fabricate bridge mold and plastic injection mold. Fabrication of an epoxy resin mold with high replication accuracy was carried out applying a three-step micro-replication procedure.

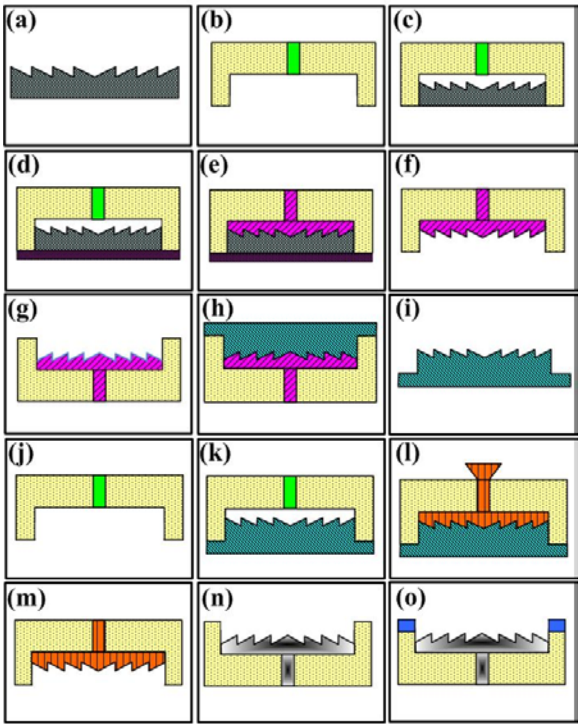

Fig. 1. Schematic illustration of process flow for fabricating a precision epoxy resin mold: a – master model; b – machining the groove and sprue of mold plate; c – placing the master model in the groove; d – pouring the silicone rubber over the master model; e – first silicone rubber mold; f – placing the first silicone rubber mold upside down in the groove; g – spraying the release agent; h – pouring silicone rubber over the first silicone rubber mold; i – second silicone rubber mold; j – cleaning the mold plate; k – placing the second silicone rubber mold in the groove; l – pouring the epoxy resin composites over the second silicone rubber mold; m – epoxy resin mold; n – post curing of epoxy resin mold; o – machining the slot of epoxy resin mold

In the first step, the first silicone rubber mold was fabricated by pouring the mixed silicone rubber resin over the master pattern. Silicone rubber was mixed with a curing agent with a mass ratio of 10 : 1 thoroughly with a stirrer. To increase the replication accuracy of the fabricated rapid tooling, avoiding the use of release agent in the rapid tooling manufacturing process is essential. In the second step, the second rubber mold was fabricated by pouring the mixed silicone rubber resin over the first silicone rubber mold. An epoxy resin mold with high replication accuracy was finally fabricated by pouring the mixed epoxy resin composites over the second silicone rubber mold. Epoxy resin composite (70-3810R, Epoxies) is composed of 70 % aluminum (Al) powder and 30 % liquid epoxy resins. A vacuum machine was employed to eliminate the air-bubbles derived from the mixing process to obtain bubble-free silicone rubber mold and epoxy resin mold in a vacuum condition. To help the epoxy resin mold reach its full mechanical and physical characteristics, the epoxy resin mold was first heated to 79 °C for 2 h to avoid causing large amount of bubbles during post cure. In this phase, the epoxy resin mold starts to become hard and cross-link becomes increasingly. The epoxy resin mold was then post cured at 149 °C for 3 h. After post cure, the fabricated epoxy resin mold has high crosslink density. The epoxy resin mold is a clone of the second silicone rubber mold and has negative microfeatures of the master pattern. After post-cure heat treatment in a convection oven (DH400, Deng Yag), the epoxy resin mold is rigid enough for plastic injection molding [20].

Fig. 2 shows the microstructures of the fabricated epoxy resin mold. Two-plate mold was used in this work because it is more cost-effective and simple mold design compared to three-plate mold, as shown in Fig. 3. The microgroove depth in the center of epoxy resin mold is approximately 62 µm. The molding experiments were performed by a plastic injection molding machine (TR20EH, Sodick) with a maximum clamping force of 196 kN. The experimental material used in this study was polymethylmethacrylate (PMMA), which is a commercial available injection-molding optical grade polymer (MH-12C07AA8, Sumitomo).

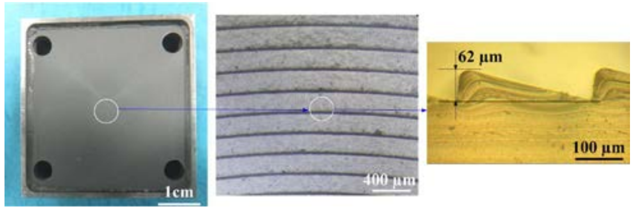

Fig. 2. Microstructures of the fabricated epoxy resin mold

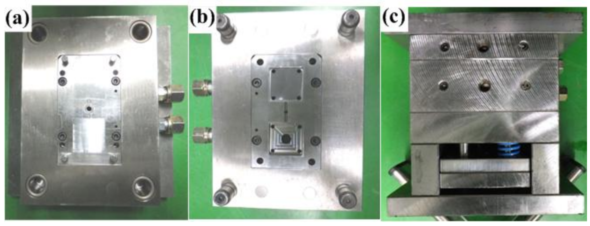

Fig. 3. Plastic injection mold: a – cavity half; b – core half; c – assembly

A set of experiments was conducted to determine the effect of the processing parameters on the replication accuracy of the injected Fresnel lens. During the micro-plastic injection molding using PMMA, 20 shots under the same operational conditions were carried out to ensure that the process was stable before samples were collected. The dimensions of Fresnel lens fabricated by micro-plastic injection molding were measured using an optical microscopy (OM) (M835, Microtech).

3. RESULTS AND DISCUSSION

In the Taguchi method, the design parameters of the system to be studied are known as the control factors or design variables, which mainly affect the output of the objective function. Yang [21] employed melt temperature, mold temperature and packing pressure as control factors to identify an optimal setting of the injection molding process. Chen et al. [22] employed injection speed as a control factor to investigate the optimum level of process parameters. Thus, four parameters, packing pressure, melt temperature, mold temperature and injection speed, were used as the control factors in this study. The L_9 was employed as an orthogonal array (OA) because it is suitable for four control factors with three levels. The values of level 2 for four control factors was determined from the data sheet provided by PMMA supplier, which was an average value of level 1 and level 3. To investigate the optimum process conditions for the plastic injection molding, three levels, namely low, middle and high values were employed in this work. Table 1 lists four control factors and their levels. Other processing parameters such as cooling time of 10 sec, injection pressure of 100 MPa, packing time of 1 sec and screw speed 30 m/min were kept constant during the experimentation.

Table 1. Control factors and their levels

Control factor		Level 1	Level 2	Level 3
A	Melt temperature (°C)	240	255	270
B	Packing pressure (MPa)	80	100	120
C	Mold temperature (°C)	70	80	90
D	Injection speed (mm/s)	10	30	50

The L_9 was employed as an orthogonal array (OA) because it is suitable for four control factors with three levels. The experimental results of dimension error based on L_9 OA are summarized in Table 2. Micro- injection molding of Fresnel lens was carried out using a micro-featured epoxy resin mold. No any defects were observed, which were confirmed by the corresponding OM examination. This shows that the microstructures of Fresnel lens can be fabricated through the fabricated epoxy resin mold using micro-injection molding.

Table 2. Experimental results of dimension error

Trial No.	Control factor				Dimension error (μm)			σ2	S/N (dB)
	A	B	C	D	1	2	3		
1	a1	b1	c1	d1	12	18	16	18.444	–23.826
2	a1	b2	c2	d2	45	42	39	13.500	–32.480
3	a1	b3	c3	d3	24	20	26	15.111	–27.409
4	a2	b1	c2	d3	15	12	16	7.278	–23.188
5	a2	b2	c3	d1	35	31	34	8.444	–30.469
6	a2	b3	c1	d2	46	41	47	17.944	–33.015
7	a3	b1	c3	d2	26	21	17	31.278	–26.709
8	a3	b2	c1	d3	41	37	45	24.000	–32.283
9	a3	b3	c2	d1	43	39	48	29.778	–32.768

In the Taguchi design method, quality characteristics can be categorized into the-smaller-the- better, the-nominal-the-best and the-bigger-the-better. In this study, the-smaller-the-better is chosen because a lower dimension error means a better dimensional accuracy of Fresnel lens fabricated by micro-injection molding. Table 3. shows the response table of signal-to-noise (S/N) ratio based on the-smaller-the- better quality characteristics. From the data in Table 3, the effects of all four control factors with their corresponding levels are graphically shown in Fig. 4. A best set of optimal combination of control factors and levels was determined because a higher S/N ratio represents a better quality characteristic. The result obtained is A1, B1, C3 and D3, i. e. packing pressure of 80 MPa, melt temperature of 240 °C, mold temperature of 90 °C and injection speed of 50 m/s.

Table 3. Response table of S/N ratio based on the-smaller-the-better quality characteristics

	Control factors			
	A	B	C	D
	Melt temperature (°C)	Packing pressure (MPa)	Mold temperature (°C)	Injection speed (mm/s)
Level 1	–27.905	–24.574	–29.708	–29.021
Level 2	–28.890	–31.744	–29.478	–30.734
Level 3	–30.586	–31.064	–28.195	–27.627

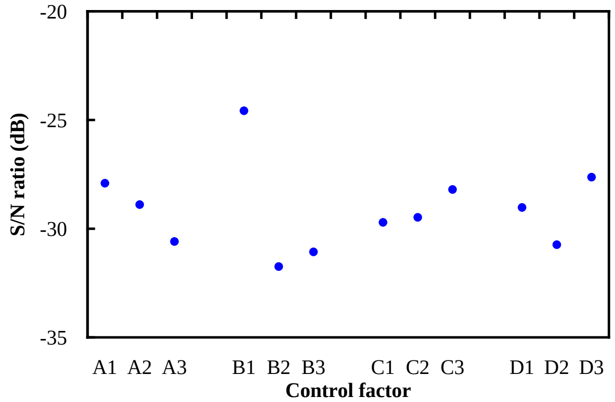

Fig. 4. S/N ratio effects for each control factor

The analysis of variance (ANOVA) is a statistical method used to separate the individual effects from all control factors. To analyze the results of the experimental designs, the ANOVA was carried out. The percentage contribution of each control factor is employed to measure the corresponding effect on the quality characteristic. The results of ANOVA are summarized in Table 4. The percentage contribution of variance was calculated by ANOVA results. As can be seen, the percentage contributions of factor b, factor d, factor a, and factor c are 76.07 %, 11.77 %, 8.93 % and 3.23%, respectively. Therefore, the control factor b, packing pressure, is the most significant factor affecting the microgroove depth of Fresnel lens. This result is consistent with the findings by Mehat and Kamaruddin [23] as well as Ozcelik and Sonat [24]. This is because Fresnel lens belongs to thin-wall part and packing pressure provides compensation of shrinkage during the plastic injection molding process. This shows that the dimensional accuracy of Fresnel lens depends significantly on the packing pressure. From the S/N ratio, a set of optimum level of process parameters can be determined. Thus, the optimum processing parameters are packing pressure of 80 MPa, melt temperature of 240 °C, mold temperature of 90 °C and injection speed of 50 m/s.

The verification test is very important in engineering analysis to validate the minimum dimension error resulted

Table 4. Results of ANOVA

		Level1	Level 2	Level 3	SS	V	DOF	ρ (%)
A	Melt temperature (°C)	27.905	28.890	30.586	11.039	5.519	2	8.93
B	Packing pressure (MPa)	24.574	31.744	31.064	93.983	46.992	2	76.07
C	Mold temperature (°C)	29.708	29.478	28.195	3.986	1.993	2	3.23
D	Injection speed (mm/s)	29.021	30.734	27.627	14.539	7.269	2	11.77

from optimization process. Thus, the final step of the Taguchi method is to conduct a verification test for examining dimensional accuracy of Fresnel lens using optimum level of process parameters. Twenty parts were injected based on the optimum level of process parameters.The microgroove height of the injected parts were measured using OM having measurement accuracy about ±1 μm and the results are shown in Fig. 5.

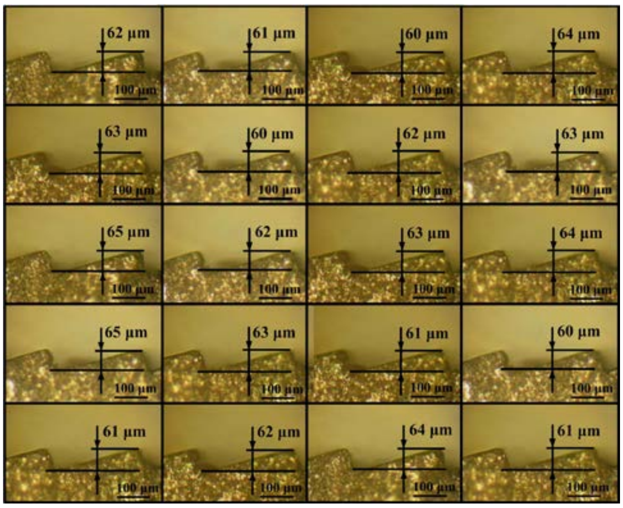

Fig. 5. Microgroove depths of the 20 confirmation samples in the verification test

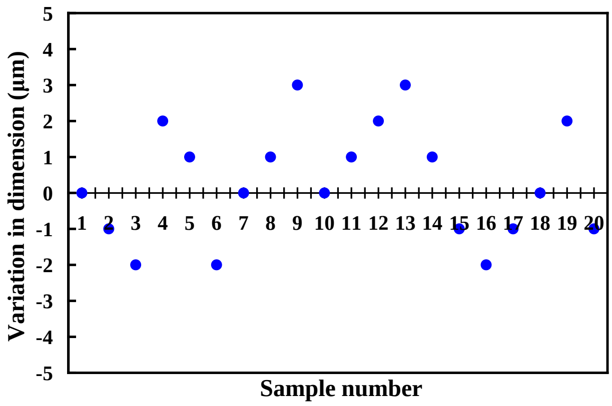

Fig. 6. Dimensional accuracy of the Fresnel lens fabricated by optimum level of process parameters

Fig. 6 shows the dimensional accuracy of the embossed Fresnel lens. The reference dimension of microgroove depth is 62 μm. As can be seen, the dimensional variations of the embossed Fresnel lens is –2 μm ÷ –3 μm. This result indicates that the Fresnel lens with the dimensional accuracy about ±3 μm can be obtained. A precision Fresnel lens with the transcription rate up to 99 % can be successfully fabricated via the developed epoxy resin mold using optimum level of process parameters because the shrinkage due to contraction of the PMMA was measured to be about 0.2 % – 0.6 %. This means that it is suitable for application in the precision machinery industry to reduce development cycle time of a new Fresnel lens or microfluidic devices [25].

4. CONCLUSIONS

Micro- injection molding of micro-featured polymer-based products has demonstrated a significant commercial potential in precision electro-optical machinery industry. This study provides a better understanding of the molding characteristics for the fabrication of precision diffractive optical elements via a precision epoxy resin mold using micro-injection molding. A major contribution of this work is that a precision epoxy resin mold has been fabricated within three days using epoxy resin composites. The main advantages of the developed epoxy resin mold include low manufacturing cost, short lead time and simple manufacturing processes. The fabricated epoxy resin mold was then tested to fabricate Fresnel lens using micro-injection molding. The Taguchi method has been demonstrated an efficient approach to determine the optimum level of process parameters for fabricating Fresnel lens using micro-plastic injection molding. According to ANOVA results, the packing pressure is the most influential factor with a contribution of about 76.07 %, which affects the microgroove depth of Fresnel lens. The optimum level of process parameters for packing pressure, melt temperature, mold temperature and injection speed are 80 MPa, 240 °C, 90 °C and 50 m/s, respectively. Confirmation tests verified that the Fresnel lens with the replication accuracy of depth about ±3 μm can be obtained using the optimum level process parameters. The results reported in this study possess industrial application values because electro-optical industries are able to greatly reduce a new Fresnel lens development cycle time for both design and production, reducing costs and increasing profit.

Acknowledgments

The authors gratefully acknowledge the financial support of the National Science Council of Taiwan under contracts nos. NSC102-2221-E-131-012 and NSC101-2221-E-131-007.

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