Journal of Materials Processing Technology 209 (2009) 5690–5701

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Robust parameter design of micro-injection molded gears using a LIGA-like fabricated mold insert

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ARTICLE INFO

Article history:
Received 29 November 2008
Received in revised form 19 March 2009
Accepted 26 May 2009

Keywords:
Micro-injection molding
Plastic Gear
Principal component analysis
Robust design
UV-LIGA

ABSTRACT

Micro-injection molding, with advantages of easy mass production and low cost, is a key technology for producing micro components. Nevertheless, a low yield rate of high-quality molded parts is common due to problems associated with geometric precision, molecular orientation, and optical properties. Solutions to such problems must consider the machine, mold design, and process parameter settings. However, optimal performance becomes relatively less attainable when process parameters deviate due to inevitable process tolerances and change in an operation environment. This study has two goals: (1) fabrication of high-precision mold inserts using UV-LIGA; and, (2) identification of robust parameters that ensure production quality. Two gear mold-inserts with outside diameters of approximate 6 mm and 4 mm, named as the 6 mm and 4 mm gears, are introduced. First, lithography of thick photoresist SU8-50 is utilized as the initial structure seed layer to electroform the Ni gear mold insert. Second, this study investigates two key geometrical dimensions-the outside diameter and tooth thickness of the molded gears. The robust optimization of multiple objectives is introduced to identify robust parameter settings with high dimensional accuracy and high yield rates for molded gears despite process parameter deviations. Experimental results indicate that electroformed Ni mold inserts have good quality and are successfully utilized in the subsequent micro-injection molding process, demonstrating the feasibility of the mold inserts fabricated using UV-LIGA. The micro-injection molding experiments suggest that mold temperature, holding pressure, and injection speed have significant effects on dimensional quality characteristics of molded gears. The robust parameters derived from the proposed method increase yield rates of the 6 mm gear from 10% to 91%, and those of the 4 mm gear from 38% to 93% in comparison with the initial point, thereby demonstrating application effectiveness.

1. Introduction

Their trend toward production miniaturization is increasing with the rapid development of micro-engineering technologies such as optical grating elements, micro-featured light-guided plates, and micro gears (Monkkonen et al., 2002; Yao and Kim, 2004; Yoshii et al., 1994). Micro-injection molding is a primary technology in micro-manufacturing due to its low cost and suitability to mass production. LIGA technology combining X-ray lithography, micro-electroforming, and micro-molding, enables mass production of precision microstructures with high aspect ratios and, thus, has been utilized to produce high-precision micro gears (Malek and Saile, 2004). However, due to high fabrication costs and limited synchrotron sources of X-ray lithography, alternative processes, such as UV-LIGA and other LIGA-like processes have been developed. Notably, UV-LIGA uses UV light for lithography and thick photoresists to achieve microstructures with high aspect ratios (Del Campo and Greiner, 2007; Tseng and Yu, 2002). Lorenz et al. (1998) applied UV-LIGA to fabricate a Ni gear-set mold insert and then to obtain plastic gears via micro-injection molding. SU8 negative resist was used in the lithographic process. The gear set consisted of a small gear with an outer diameter of 860 μm and thickness of 460 μm, and a relatively larger gear with an outer diameter of 3 mm and thickness of 220 μm. They verified that plastic gears have a better surface finish than micro molds fabricated by wire electrical discharge machining (wire EDM). Due to the advantage of high precision of microstructures manufactured using UV-LIGA, this work uses UV-LIGA to fabricate Ni gear molds for a study of the micro-injection molding process.

Many factors can adversely affect the replication quality of molded parts during micro-injection molding. A sub-set of these factors is called process factors; these factors are very important and have been studied extensively. Generally, the process factors studied are melt and mold temperatures, injection speed, injection and holding pressures, and cooling time. With the development of the micro-injection molding technology, new machines for fabri-

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doi:10.1016/j.jmatprotec.2009.05.032

cating miniature parts with micro-features have been developed. Additionally, other process factors have been analyzed, such as metering size and a small forward movement of the injection plunger for controlling holding pressure, in an attempt to improve process performance (Zhao et al., 2003).

Process parameter design plays a crucial role in ensuring the quality of molded parts prior to production. Conventional process parameter settings for injection molding are based on experimental data, computer-aided simulations, and operator's experience (Bozzelli, 2003; Nirkhe and Barry, 2003). In the case that the quality characteristic of molded parts using the current parameters setting is close to specification limits, the production process will be influenced by environmental noise, which increases the defect rate. In this case, production process parameters are not robust. Approaches such as the Taguchi method and response surface method (Goupy, 2005; Huang and Lin, 2008a) have been developed to target part quality by designing effective experiments to identify optimal process parameters (Dowlatshahi, 2004; Liu and Manzione, 1996; Viana et al., 1998). The Taguchi method is well known for its design of effective experiments; however, optimal process parameters are confined to one single quality characteristic at a time when analyzing optimal process parameters. In reality, identifying ideal process parameters and focusing on multiple quality characteristics are difficult but generally required.

In investigating multiple quality characteristics, *i.e.*, a large number of correlated quality characteristics, information collected from experiments may be contradictory, and, consequently, data analysis may be difficult. Principal component analysis (PCA) allows data containing information of multiple quality characteristics to be converted into several independent quality indicators. Some of these indicators are then selected to construct a composite quality indicator, which represents the mathematical function of the required multiple quality characteristics. If PCA can be further integrated with the Taguchi method, the resulting methodology will be practical and efficient in solving problems of multiple quality characteristics (Antony, 2000). However, PCA has one significant shortcoming: if multiple principal components exists and their individual eigenvalues are greater than one being selected, a feasible solution that satisfies each quality indicator is not guaranteed. To overcome this problem, Liao (2006) developed the weighted principal component (WPC) method and estimated quality by the accountability proportion of each principal component. Another approach is the desirability function (DF), developed by Derringer and Suich (1980), which redefines composite quality.

To satisfy high dimensional accuracy and high yield rate for molded gears despite process parameter deviations, the regression model proposed by Huang and Lin (2008b) for setting robust injection molding parameters was adopted in this study, and the WPC and DF methods for generating composite quality indicators were compared. The design of experiment (DOE) and ANOVA methods were then applied to choose the major parameters as adjustment factors. Moreover, a two-level statistically designed experiment with the least squared error method was used to generate a regression mode comprising part quality and adjustment factors. Based on this mathematical model, the steepest decent method was employed to search for optimal process parameters for micro-injection molding gears with outside diameters of approximate 6 mm and 4 mm, which are named as the 6 mm and 4 mm gears in this study.

2. Fabrication of gear mold insert using LIGA-like processes

The UV-LIGA process is utilized to fabricate two Ni gear mold inserts with outer diameters of approximate 6 mm and 4 mm, respectively. Table 1 lists fabrication parameters. The schematic process flow (Fig. 1) is described in detail as follows.

Table 1
The UV-LIGA process parameters.

Process	Parameters
Intermediate and seed layers	Ti 200 Å and Pt 1000 Å
Resist thickness	500 μm
Soft baking	6–9 h at 65 °C
Exposure dosing	400 mJ/cm^2
Post exposure baking	0.5–1 h at 95 °C
Development time	0.5–1 h
Hard baking	5–30 min at 150–250 °C
Electroforming material	Ni

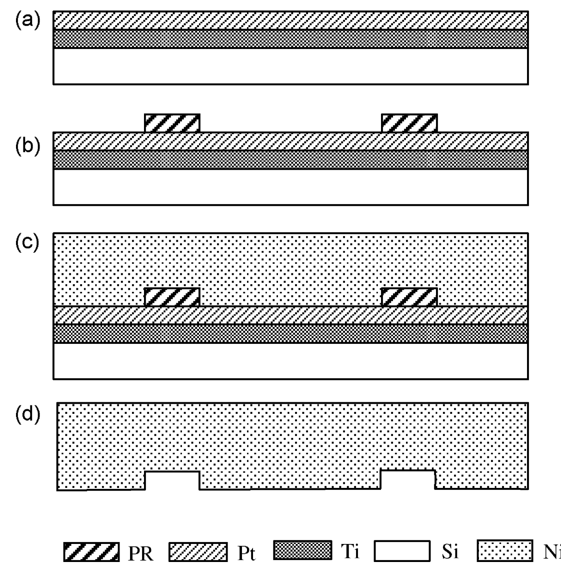

Fig. 1. Process flow for fabricating the gear mold insert: (a) use PECVD to sputter a 200 Å bonding layer Ti and 1000 Å conducting layer Pt; (b) pattern a 500 μm SU8 gear by photolithography; (c) deposit Ni on the SU8 gear by electroforming; and, (d) separate the Ni layer and apply post processes to obtain the Ni gear mold insert.

(1) A 200 Å Ti layer and a 1000 Å Pt layer are deposited in sequence on a silicon substrate by an E-beam evaporator. The Pt layer is used as the conductive seed layer in the electroforming process, whereas the Ti layer functions as an adhesive layer between the substrate and Pt layer.
(2) The 500 μm-thick SU8 resist is spin-coated onto the substrate, and patterned into a resist gear by lithography.
(3) The Ni is electroplated onto the substrate with the SU8 gear pattern to generate a Ni gear mold insert. To reduce current crowding effect (Romankiw, 1997) that typically causes the deposition rate near the edges of the substrate to increase, a plastic shielding sheet is attached to the substrate edges such that deposition density becomes relatively uniform over the entire substrate.

The Ni gear mold insert is ground and then cut by wire EDM to fit into the mold for micro-injection molding.

Fig. 2(a)–(d) shows SEM photographs of the SU8 resist gears produced by lithography. The surface finish for both the 6 mm and 4 mm SU8 gears is good. Fig. 3 shows the resultant Ni gear mold inserts with good surface quality.

3. Robust parameter design method

Fig. 4 shows the robust parameter design method utilized in this study. This design method has three phases: (1) setting the composite quality indicator; (2) executing 2^3 full factorial

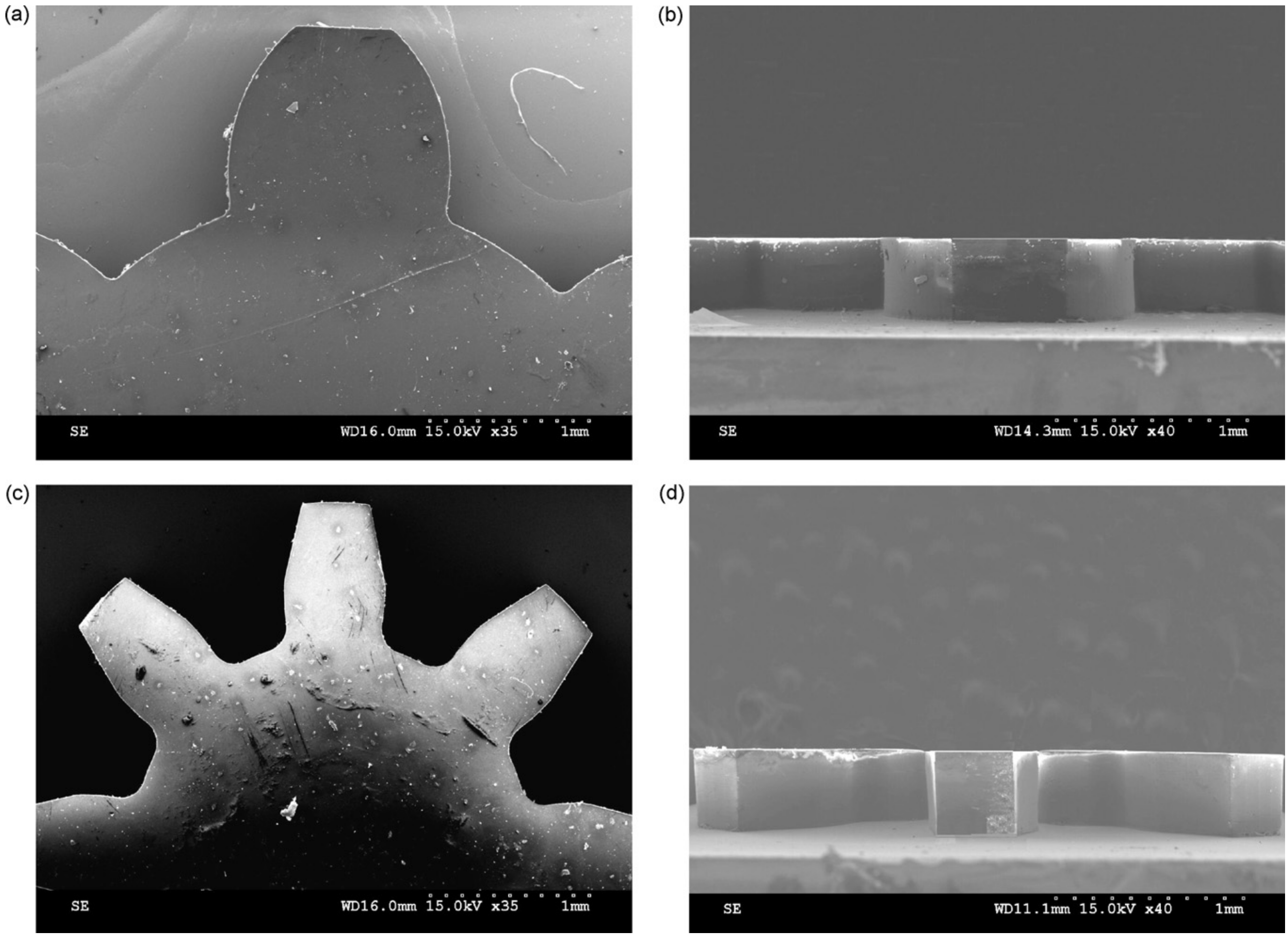

Fig. 2. SEM photographs of the SU8 gear mold: (a) the 6 mm SU8 gear structure (top view), (b) the 6 mm SU8 gear structure (side view), (c) the 4 mm SU8 gear structure (top view), and (d) the 4 mm SU8 gear structure (side view).

experiments; and, (3) searching for robust process parameters. The details of these three phases are described as follows.

3.1. Phase 1: setting the composite quality indicator

Initially, data containing information of multiple quality characteristics were collected and normalized to generate dimensionless indices, which fall in the range of 0–1. Second, the DF and WPC methods were individually applied during this phase to convert observed data into a composite quality indicator, which represents a mathematical model of multiple quality characteristics. The desirability function method proposed by Derringer and Suich (1980) suggests that the composite quality indicator can be defined as

$$\phi_{\mathrm{D}} = \prod_{j=1}^{p} (Y_{ij}^{*})^{1/p}, \quad j = 1, 2, \ldots, p \tag{1}$$

where Y_{ij}^{*} is the normalized observed index for the ith experimental run and jth quality characteristic, and 'p' is the number of quality characteristics. The value of ϕ_{D} is zero when any Y_{ij}^{*} is zero, and is 1 only when all Y_{ij}^{*} are 1.

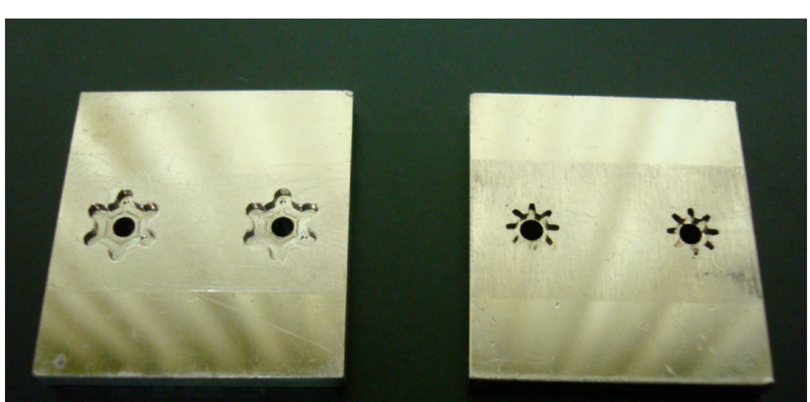

Fig. 3. Ni mold inserts for the 6 mm (left) and 4 mm (right) gears.

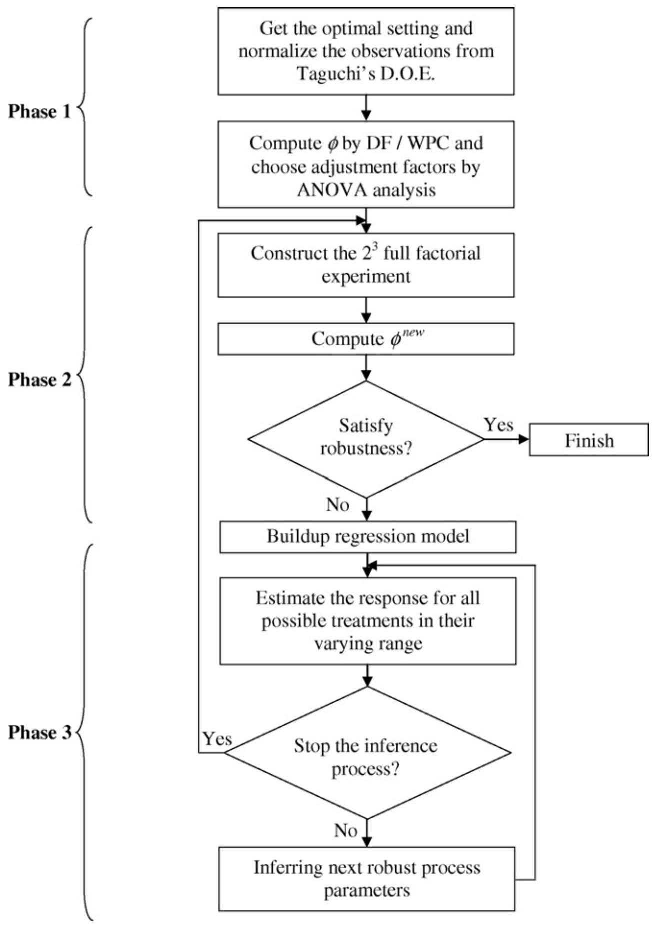

Fig. 4. Flowchart of the robust parameter design method.

For the WPC method, the normalized data were then used to construct a variance-covariance matrix '$\boldsymbol{A}$', which is

$$A = \begin{bmatrix} R_{1,1} & R_{1,2} & \dots & R_{1,p} \\ R_{2,1} & R_{2,2} & \dots & R_{2,p} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n,1} & R_{n,2} & \cdots & R_{n,p} \end{bmatrix} \tag{2}$$

$$R_{k,l} = \frac{Cov(Y^*_{i,k}, Y^*_{i,l})}{\sqrt{Var(Y^*_{i,k})Var(Y^*_{i,l})}} \tag{3}$$

where n is the number of experimental runs. The eigenvectors and eigenvalues of matrix $\boldsymbol{A}$ are computed, and are represented by $\boldsymbol{V_j}$ and λ_j, respectively.

In PCA, eigenvector $\boldsymbol{V_j}$ is the weighting vector of j number of quality characteristics of the jth principal component. For instance, when Q_j is the jth quality characteristic, the jth principal component 'ϕ_j' is treated as a quality indicator with the required quality characteristics:

$$\phi_j = V_{1j}Q_1 + V_{2j}Q_2 + \cdots + V_{jj}Q_j = V_j'Q \tag{4}$$

Notably, each principal component ϕ_j represents a certain degree of explanation of variation in quality characteristics, namely, the accountability proportion. Thus, the weighted principal component ϕ_W is defined as

$$\phi_W = \sum_{j=1}^{j} AP_j \times \phi_j \quad j = 1, 2, \cdots, p \tag{5}$$

Selection of adjustment factors was based on the contribution percentage of experimental factors to composite quality indicator ϕ_C, as determined by ANOVA. The adjustment factors have two distinct characteristics. (1) A change in adjustment factors due to environmental interference strongly affects part quality. If adjustment factors are controlled, the production of a quality product is assured. By varying these adjustment factors, this study identified a process window that allows the chosen factors to be altered within the window; thus, the molded parts met quality specifications. (2) When some parts were molded with process parameters within the process window failed to reach the desired quality, alterations were made on the range of the process window to meet the quality requirement.

In this phase, the composite quality indicator was generated by many quality indicators with different adjustment factors; however, only the first three most important adjustment factors were selected in this work. These factors were used again in Phases 2 and 3 to search for the optimal combination of process parameters.

3.2. *Phase 2: executing 2^3 full factorial experiments*

As mentioned, the quality of injection parts can vary with due to environmental noise. Thus, a robust process window is needed in which adjustment factors are free to move around, such that the quality characteristics satisfy quality specification limits. By varying the adjustment factors generated by environmental noise and performing 2^3 full factorial experiments, a robust process window was identified. The experimental runs were designed using a combination of extreme points of a three-dimensional process window. When a defect occurs at the extreme points in the process window, a superior region can be found by applying the steepest decent method to search for a new location of parameters settings.

3.3. *Phase 3: searching for robust process parameters (Huang and Lin, 2008a)*

Through establishing a regression model based on the relationship between the process parameters and quality observations, the steepest decent method was employed to determine the distance and direction to the quality target. It was assumed that a quality observation, y and k number of process parameters, significantly affect quality, such as x_1, $x_{2,}\cdots$, x_k. The sample datum of the full factorial experiment in the previous phase could be used to fit a regression model. Therefore, the designed matrix of the experiment can be used to obtain the data sample for fitting a regression model. The matrix is

$$Y = X\beta + \varepsilon \tag{6}$$

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}; \quad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}; \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix} \tag{7}$$

where $\boldsymbol{Y}$ is the vector of observation, which may be ϕ_D^{new} or ϕ_W^{new}; $\boldsymbol{X}$ is the matrix of experimental runs; x_{nk} is the k^{th} process parameter in the experimental run 'n'; $\boldsymbol{\beta}$ is the vector of estimated coefficients in the regression model; and $\boldsymbol{\varepsilon}$ is the random error vector.

The $\boldsymbol{\beta}$ vector can be estimated using the least squared error method as follows:

$$\beta = \frac{1}{2}(X'X)^{-1}X'Y \tag{8}$$

The composite equation of the relationship between process parameters and product quality can then be determined. In addition, there is a need to convert $\boldsymbol{Y}$ and the matrix $\boldsymbol{X}$ in Eq. (7) into Eq. (8) to obtain the $\boldsymbol{\beta}$ coefficient in the regression model.

The steps in Phase 3 are as follows.

Step 1: Establish the regression model: Eq. (6) models the relationship between process parameters and part quality. The $\boldsymbol{Y}$ and $\boldsymbol{X}$ in Eq. (7) can be substituted into the following equations:

$$Y=\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_8 \end{bmatrix};\quad X=\begin{bmatrix} 1 & -1 & -1 & -1 & 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \\ 1 & -1 & 1 & 1 & -1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (9)$$

The $\boldsymbol{X}$ matrix was generated with two values, 1 and -1, which represent the upper and lower levels of each control factor, respectively. The second, third, and fourth columns represent levels of x_1, x_2, and x_3 control factors, respectively. The fifth, sixth, and seventh columns represent the levels of interaction effects of x_1 to x_2, x_1 to x_3, and x_2 to x_3, respectively. The eighth column stands for the interaction effects among x_1, x_2, and x_3. By inputting vector $\boldsymbol{Y}$ and matrix $\boldsymbol{X}$ into Eq. (8), one obtains the coefficient vector of the regression model, $\boldsymbol{\beta}$.

Step 2: Estimate the responses for all possible treatments in the varying ranges: Use the set-point of process parameters (or predicted points of robust molding parameters) and the least resolution of machine control as the basis for arranging all possible treatments in varying ranges. For example, if there are three adjustment factors and the upper and lower limits are five times the least resolution of the injection molding machine, the number of treatments is 5^3.

Step 3: Determine whether the inference process should be continued: This step determines whether the inference process of the robust molding parameters should be stopped. By substituting all treatments to construct coefficient vectors in the regression model and generate predicted values, stopping the inference process has two conditions: either all predicted values meet the quality specifications; or, some predicted values do meet the quality specifications. In the latter case, the set-point should be selected in the inference process; then go to Step 4. For the former case, return to Phase 2 to assess its robustness.

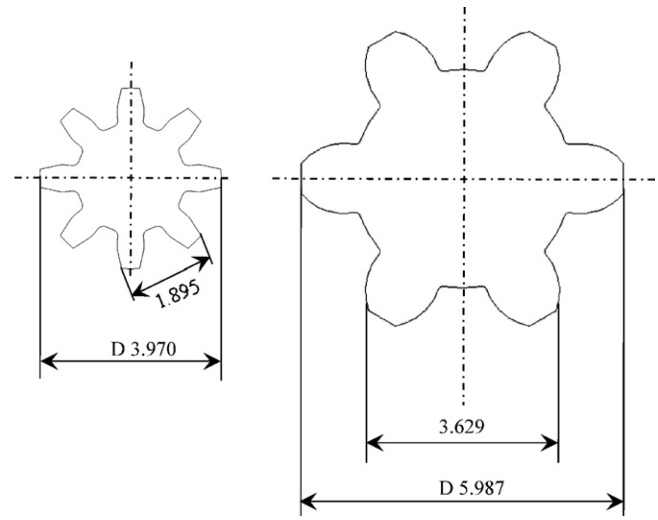

Fig. 5. Dimensions of the mold inserts of the 4 mm and 6 mm gears.

Step 4: Infer the next robust molding parameter: Set the search direction using the steepest decent method. The forward distance relies on the least resolution of machine control. Return to Step 2.

4. Experimental setup

The quality objective for robust parameter design of micro-injection molding gears is smaller-the-better, which is defined as the dimensional error of the outside diameter and tooth thickness. The theoretical dimensions of the gear molds (Fig. 5) are 5.987 mm in outside diameter and 3.629 mm in tooth thickness for the 6 mm gear, and 3.970 mm in outside diameter and 1.895 mm in tooth thickness for the 4 mm gear. Both gears have two cavities in each mold. The stamper for injection molding gears is fixed to the mold core and filled by a pinpoint gate. The molding material is POM (specification: TEPCON M90 made in Taiwan) with a shrinkage rate of 0.74%. In reference to ISO IT5–10, the tolerance limits of the 6 mm gear are 5.937–5.943 mm in outside diame-

Table 2
The L_{18} orthogonal array (the 6 mm gear).

Exp. no.	A	B	C	D	E	F	G	H	1st quality (Avg)	1st quality (St. Dev.)	1st quality (S/N)	2nd quality (Avg)	2nd quality (St. Dev.)	2nd quality (S/N)
1	10	80	190	500	1.0	60	79	10	5.9212	0.0023	33.19	3.5370	0.0019	20.73
2	10	80	195	600	1.5	70	80	15	5.9275	0.0028	36.04	3.5427	0.0016	21.28
3	10	80	200	700	2.0	80	81	20	5.9313	0.0043	38.10	3.5551	0.0020	22.63
4	10	90	190	500	1.5	70	81	20	5.9253	0.0029	34.95	3.5466	0.0026	21.68
5	10	90	195	600	2.0	80	79	10	5.9323	0.0032	39.09	3.5529	0.0025	22.37
6	10	90	200	700	1.0	60	80	15	5.9333	0.0023	40.05	3.5611	0.0021	23.36
7	10	100	190	600	1.0	80	80	20	5.9352	0.0038	41.23	3.5568	0.0026	22.82
8	10	100	195	700	1.5	60	81	10	5.9360	0.0027	42.49	3.5597	0.0019	23.18
9	10	100	200	500	2.0	70	79	15	5.9338	0.0045	39.83	3.5405	0.0011	21.06
10	30	80	190	700	2.0	70	80	10	5.9222	0.0042	33.06	3.5496	0.0016	22.00
11	30	80	195	500	1.0	80	81	15	5.9305	0.0030	37.85	3.5431	0.0016	21.31
12	30	80	200	600	1.5	60	79	20	5.9255	0.0035	34.98	3.5602	0.0012	23.25
13	30	90	190	600	2.0	60	81	15	5.9316	0.0026	38.63	3.5531	0.0021	22.39
14	30	90	195	700	1.0	70	79	20	5.9368	0.0040	42.74	3.5720	0.0015	**24.87***
15	30	90	200	500	1.5	80	80	10	5.9413	0.0038	47.77	3.5493	0.0016	21.97
16	30	100	190	700	1.5	80	79	15	5.9427	0.0026	**51.74***	3.5532	0.0019	22.41
17	30	100	195	500	2.0	60	80	20	5.9375	0.0034	43.88	3.5516	0.0025	22.22
18	30	100	200	600	1.0	70	81	10	5.9339	0.0039	40.11	3.5396	0.0010	20.97

A: back pressure (kg/cm^2); B: mold temperature (°C); C: barrel temperature (°C); D: holding pressure (kg/cm^2); E: holding time (s); F: injection speed (%); G: metering size (mm); H: cooling time (s).

1st quality: Error of outside diameter (unit: mm); 2nd quality: Error of tooth thickness (unit: mm).

* The best performance in quality; number of samples: 20.

ter, and 3.571–3.629 mm in tooth thickness. The tolerance limits of the 4 mm gear are 3.965–3.970 mm in outside diameter, and 1.847–1.895 mm in tooth thickness. The molding machine, an ITRI MIRL-5T, which is made in Taiwan and is electrically driven, has maximal clamping force of 5 tons, maximal shot volume of 2 cm^3, maximal metering size of 100 mm, maximal injection speed of 800 mm/s, and maximal injection pressure of 2500 kg/cm^2.

Table 2 shows Taguchi's L_{18} orthogonal array used in the experiment. The control factors are back pressure, mold temperature, barrel temperature, holding pressure, holding time, injection speed, metering size, and cooling time. Twenty samples were used in each experimental run. The molded gears were measured by the profile projector (Nikon V-12B with a 0.1 μm resolution).

5. Analysis of experimental results

To identify robust parameters that ensure product quality, experiments for molding two gear mold inserts with outside diameters of approximate 6 mm and 4 mm were conducted. Experimental results are described as follows.

5.1. Micro-injection molding of 6 mm gears

Table 2 summarizes the L_{18} experimental results of injection molding the 6 mm gears. Errors in outside diameter and tooth thickness are called first quality and second quality, respectively. Among the 18 possible combinations of Taguchi's orthogonal array, the best combination for the first quality is at Exp. No. 16, and that for second quality is at Exp. No. 14. Moreover, ANOVA results (Table 3) indicate that mold temperature, injection speed, and back pressure markedly affect first quality. Nevertheless, holding pressure, cooling time, and mold temperature are significant factors for second quality.

To satisfy quality requirements for outside diameter and tooth thickness, the composite quality indicators must be derived. The average values of first and second qualities were further normalized, used to construct the variance-covariance matrix, and then to calculate eigenvalues through PCA. Table 4 presents the obtained eigenvalues, accountability proportions, and eigenvalues. The eigenvectors of first quality and second quality with the corresponding weights of the first and second principal component were $[0.707, 0.707]^T$ and $[0.707, -0.707]^T$, respectively. These vectors were substituted into Eq. (4) to derive the first principal component ϕ_1, and the second first principal component ϕ_2. The accountability proportions corresponding to the first and second weighting factors of the WPC are 0.645 and 0.355, respectively.

Table 4
Calculation of composite quality indicators in the 6 mm gear micro-injection molding experiment.

Exp. no.	ϕ_1	ϕ_2	ϕ_C	ϕ_W	ϕ_D
1	0.00	0.00	0.00	0.00	0.00
2	0.20	0.01	0.22	0.14	0.14
3	0.51	−0.14	0.37	0.28	0.35
4	0.23	−0.10	0.13	0.11	0.15
5	0.50	−0.05	0.45	0.31	0.35
6	0.71	−0.19	0.52	0.39	0.48
7	0.66	−0.05	0.61	0.41	0.47
8	0.77	−0.06	0.71	0.48	0.54
9	0.31	0.20	0.51	0.27	0.17
10	0.23	−0.21	0.02	0.07	0.07
11	0.28	0.08	0.36	0.21	0.19
12	0.50	−0.36	0.14	0.19	0.24
13	0.49	−0.08	0.41	0.29	0.34
14	1.07	−0.34	0.73	0.57	**0.72***
15	0.77	0.34	1.11	0.62	0.48
16	0.99	0.42	**1.41***	**0.79***	0.64
17	0.66	0.15	0.81	0.48	0.46
18	0.30	0.22	0.53	0.28	0.15

$\phi_C = \phi_1 + \phi_2$: composite quality indicators of CPC method.
ϕ_W: composite quality indicators of WPC method.
ϕ_D: composite quality indicators of DF method.
The eigenvalue, eigenvector, accountability proportion of the principal component ϕ_1 are 1.290, $[0.707, 0.707]^T$, and 0.645, respectively.
The eigenvalue, eigenvector, accountability proportion of the principal component ϕ_2 are 0.709, $[0.707, -0.707]^T$, and 0.355, respectively.
* The best performance in quality.

Table 3
The ANOVA results (the 6 mm gear).

The 1st quality (error of outside diameter)							
SV	DOF	SS	Var.	F	Confidence	PSS	CP
A	1	38.13	38.13	5.27	95.54	30.89	7.84
B	2	178.85	89.43	12.35	99.80	164.37	41.70
C	2	7.70					
D	2	28.90	14.45	2.00	81.35	14.42	3.66
E	2	21.84					
F	2	75.93	37.96	5.24	97.23	61.45	15.59
G	2	10.90					
H	2	7.36					
Pooled error	10	72.40	7.24			123.08	31.22
Total	17	394.22					100.00
The 2nd quality (error of tooth thickness)							
SV	DOF	SS	Var.	F	Confidence	PSS	CP
A	1	0.29					
B	2	2.65	1.32	3.64	93.86	1.92	10.57
C	2	0.88					
D	2	7.54	3.77	10.34	99.70	6.81	37.45
E	2	0.18					
F	2	0.89					
G	2	0.54					
H	2	3.98	1.99	5.46	97.75	3.25	17.90
Pooled error	11	4.01	0.36			6.20	34.08
Total	17	18.18					100.00

A: back pressure (kg/cm^2); E: holding time (s); B: mold temperature (°C); F: injection speed (%); C: barrel temperature (°C); G: metering size (mm); D: holding pressure (kg/cm^2); H: cooling time (s).
SV: source of variation; DOF: degrees of freedom; SS: sum of squares; Var.: variation; PSS: pure of sum squares; CP: contribution percentage.

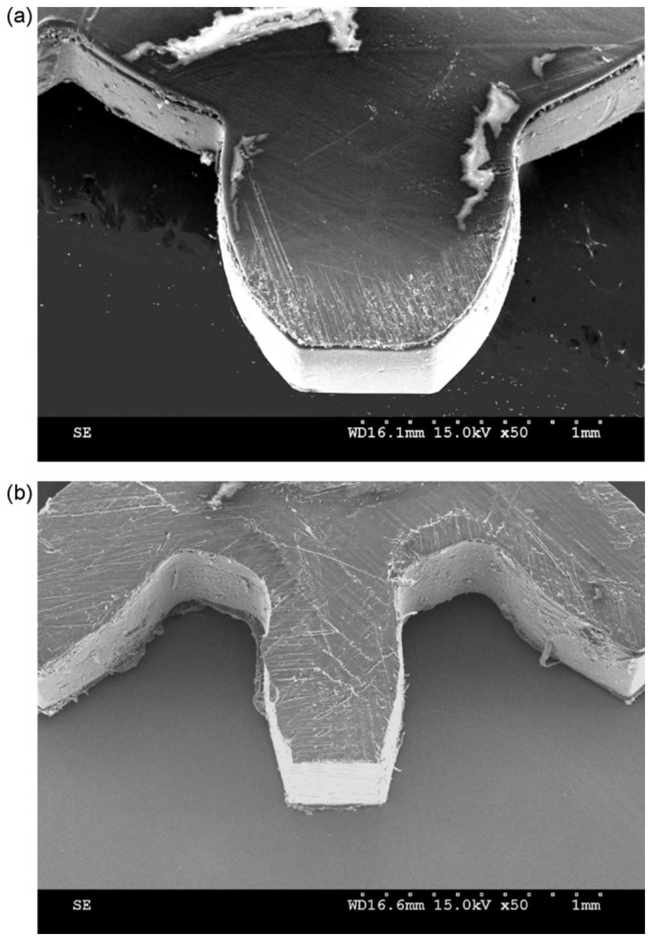

Fig. 10. The SEM photographs of micro-injection molded gears: (a) the 6 mm gear and (b) the 4 mm gear.

micro-injection molded gears generated with the robust parameter design.

6. Conclusions

This work presents a novel robust parameter search method for meeting the requirements of multiple quality characteristics in micro-molded parts. Two gear mold inserts with outside diameters of approximate 6 mm and 4 mm are used to investigate two key geometrical dimensions of a molded gear, outside diameter and tooth thickness. The UV-LIGA process is employed instead of LIGA in fabricating the Ni gear mold inserts to take advantage of its easy access and low cost. The thick photoresist SU8 is utilized to generate 500 μm-thick resist molds. Electroforming is then conducted to produce the Ni gear mold inserts. Fabrication results demonstrate that the Ni mold inserts have good surface quality and can be successfully utilized in the subsequent micro-injection molding process, demonstrating the feasibility of mold inserts fabricated using UV-LIGA. The following conclusions are based experimental results.

(1) The significant factors for outside diameter are mold temperature, injection speed, and back pressure, whereas the significant factors for tooth thickness are holding pressure, cooling time, and mold temperature.
(2) Mold temperature, holding pressure, and injection speed give significantly affect multiple quality characteristics for the 6 mm gear. Mold temperature, holding pressure, and cooling time significantly affect multiple quality characteristics for the 4 mm gear.
(3) Compared with the CPC and WPC methods, the DF approach performs best in representing the composite quality indicator.
(4) Experimental results of gear micro-injection molding demonstrate that the proposed approach in searching for optimal process parameters generates over 91% qualified products and was superior to the Taguchi method in terms of environmental influence.

In summary, the proposed robust parameter design method can effectively solve problems with multiple quality characteristics and, thus, significantly improves the stability of the micro-injection molding process and increases its yield rate.

Acknowledgements

The authors would like to acknowledge the financial support from National Science Council, Taiwan, under the project number NSC 95-2516-S-327-004. Ted Knoy is appreciated for his editorial assistance.

References

Antony, J., 2000. Multi-response optimization in industrial experiments using Taguchi's quality loss function and principal component analysis. Qual. Reliab. Eng. Int. 16, 3–8.
Bozzelli, J.W., 2003. Injection Molding Process Optimization and Documentation. ANTEC, Nashville, TN, United States, pp. 534–538.
Del Campo, A., Greiner, C., 2007. SU-8: a photoresist for high-aspect-ratio and 3D submicron lithography. J. Micromech. Microeng. 17, 81–95.
Derringer, G., Suich, R., 1980. Simultaneous optimization of several response variables. J. Qual. Technol. 12, 214–219.
Dowlatshahi, S., 2004. An application of design of experiments for optimization of plastic injection molding processes. J. Manuf. Technol. Manage. 15, 445–454.
Goupy, J., 2005. What kind of experimental design for finding and checking robustness of analytical methods? Anal. Chim. Acta 544, 84–190.
Huang, M.-S., Lin, T.-Y., 2008a. An innovative regression model-based searching method for setting the robust injection molding parameters. J. Mater. Process. Technol. 198, 436–444.
Huang, M.-S., Lin, T.-Y., 2008b. Simulation of a regression-model and PCA based searching method developed for setting the robust injection molding parameters of multi-quality characteristics. Int. J. Heat Mass Transfer 51, 5828–5837.
Liao, H.C., 2006. Multi-response optimization using weighted principal component. Int. J. Adv. Manuf. Technol. 27, 720–725.
Liu, C., Manzione, L.T., 1996. Process studies in precision injection molding: II. Morphology and precision in liquid crystal polymers. Polym. Eng. Sci 36, 576–585.
Lorenz, H., Despont, M., Vettiger, P., Renaud, P., 1998. Fabrication of photoplastic high-aspect ratio microparts and micromolds using SU-8 UV resist. Microsystem Technol. 4, 143–146.
Malek, C.K., Saile, V., 2004. Applications of LIGA technology to precision manufacturing of high-aspect-ratio micro-components and -systems: a review. Microelectronics J. 35, 131–143.
Monkkonen, K., Hietala, J., Paakkonen, P., Paakkonen, E.J., Kaikuranta, T., Pakkanen, T.T., Jaaskelainen, T., 2002. Replication of sub-micron features using amorphous thermoplastics. Polym. Eng. Sci. 42, 1600–1608.
Nirkhe, C.P., Barry, C.M.F., 2003. Comparison of Approaches for Optimizing molding Parameters. ANTEC, Nashville, TN, United States, pp. 3534–3538.
Romankiw, L.T., 1997. Path: From electroplating through lithographic masks in electronics to LIGA in MEMS. Electrochimica Acta. 42, 2985–3005.
Tseng, F.-G., Yu, C.-S., 2002. High aspect ratio ultrathick micro-stencil by JSR THB-430N negative UV photoresist. Sens. Actuators A 97–98, 764–770.
Viana, J.C., Kearney, P., Cunha, A.M., 1998. Improving Impact Strength of Injection Molded Plates through Molding Conditions Optimization: A design of Experiments Approach. ANTEC, Atlanta, GA, United States, pp. 646–650.
Yao, D., Kim, B., 2004. Scaling issues in miniaturization of injection molded parts. J. Manuf. Sci. Eng. 126, 733–739.
Yoshii, M., Kuramoto, H., Kato, K., 1994. Experimental study of transcription of minute width grooves in injection molding. Polym. Eng. Sci. 34, 1211–1218.
Zhao, J., Mayes, R.H., Chen, G., Xie, H., Chan, P.S., 2003. Effects of process parameters on the micro molding process. Polym. Eng. Sci. 43, 1542–1554.