OPTIMIZATION OF MULTI FACTORS FOR INJECTION-MOULDED MICRO GEAR VIA NUMERICAL SIMULATION INTEGRATED WITH THE TAGUCHI METHOD AND PRINCIPAL COMPONENT ANALYSIS

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ABSTRACT: Many factors need to be considered in producing micro gear by means of injection moulding process including material selection, part and mould design as well as processing parameters. Inappropriate combination of these factors can cause numerous production problems such as occurring of defects, long lead time, much scrap and high production cost. Therefore, the aim of this study is to evaluate the effects of different material for micro gear, gate types, size of gear as well as processing parameters on the multi quality characteristics of the micro gear. The simulation was conducted by integration of Taguchi L27 orthogonal array and principal component analysis. The result of main effect analysis exhibited that the optimal combination of factors that resulted in minimum sink index, volumetric shrinkage and deflection was A3B3C2D3E1F1G1H1I3. Meanwhile, from the ANOVA, gate type was found out to be the most significant factor in minimizing the multi quality characteristic of the simulated micro gear. The findings of this study should be benefited to the gear industry particularly in improving the quality of micro gear where the use of micro gear in microsystem is accelerating nowadays.

KEYWORDS: *Micro Gear; Simulation; Injection Moulding; Taguchi Optimization Method; Principal Component Analysis*

1.0 INTRODUCTION

Gears have been used for more than three thousand years and are imperative devices in all manners of machinery used to date including in office equipment, machine tools as well as in variety of industries, such as automotive, oil and gas industry, transportation, marine and aerospace [1]. A variety of cast irons, powder-metallurgy material, and nonferrous alloys are used in gears [2-3]. To date, plastic have promulgated readily throughout the modern world due their intrinsic properties such as their light weight, versatility and durability. With these advantageous characteristics, plastic have gained attention for their potential to replace other materials in gear manufacturing.

Plastic gears are continuing to displace metal gears in a variety of applications [4-7]. The evolution of plastic gears in power and motion transmission application manifests itself in consumer electronic items, including copiers, printers, scanners, and washing machines. The resourcefulness of plastic materials has encouraged manufacturers of automotive components to use plastic gears, particularly in windshield wipers, power car seats and windows, for more light weight and cost-effective drive-train design [8-9].

Plastic gears can be manufactured by either machining or injection moulding. The machining of plastic gears involves most of the same processes used in the machining of metal gears, such as milling or hobbing [10]. With the continuous expansion of advanced technology, plastic injection moulding, on the other hand, has proven to be a considerably more economical means of mass production needed to meet the rapidly rising market demand for plastic gearing in various application [11]. However, the production of plastic micro gears via injection moulding process is still new and work on injected moulded plastic micro gear is fewer reported. Producing plastic micro gear by injection moulding is becoming increasingly more challenging for today’s plastic gear industry to manufacture precision micro gearing component within tight tolerance limits. The current research related to plastic micro gear can be found from the work of Hakimian and Sulong [12] for example, investigated the effect of injection molding parameters and the types of thermoplastics composites (amorphous or crystalline based polymer matrix) on the shrinkage and warpage properties of four cavities micro gears through numerical simulation using the Taguchi method. They reported the highest improvement percentages in the shrinkage and warpage analyses were obtained from the PPE/PS and the PC/ABS, respectively. The importance of plastic micro gears is continuously increasing in multiple industries such as in medical and automobile industry [13]. Considering the great importance of injection moulding in plastic micro gear manufacturing, it is a vital to understand the basic of the injection moulding process in order to produce good quality injection moulded plastic micro gears. Therefore, the aim of this study is to investigate and evaluate the effects of different plastic material for micro gear, types of gate, size of gear as well as processing parameters on the quality of injected micro gear.

The processing parameters that will be considered in this work including filling pressure, injection time, injection pressure, cooling time and melting temperature. In order to solve the multi quality characteristics problem, the integration of the Taguchi method and principal component analysis (PCA) will be adopted in conducting the simulation. The proposed optimization method will be an attempt in improving the quality of plastic injection moulded micro gear from the manufacturing point of view. Therefore, the implementation of trial and error method in controlling the influential factors which would incurred high production cost and long set up times can be avoided.

2.0 METHODOLOGY

A micro spur gear, with an overall length of 5 mm, a gear thickness of 0.5 mm, and a teeth number of 8, was designed in Solidworks 2009 and then was used as a model, using a 3D mesh type with the aspect ratio maximum of 6.69, match percentage of 88.5% and reciprocal percentage of 91.7%. Figure 1 shows the geometry and specification of the spur micro gear.

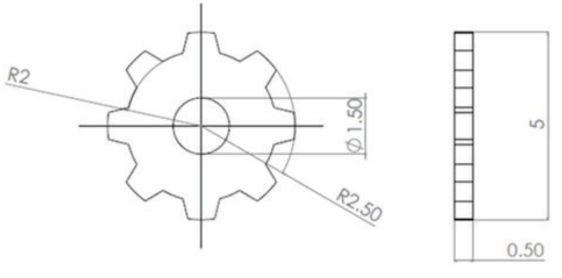

Figure 1: Geometry and specification of the spur micro gear

In this study, the Moldflow Plastic Insight (MPI) was used to conduct the numerical simulation for the 3D mesh micro spur gear model. The robust parameter design of Taguchi method and principal component analysis (PCA) were integrated in conducting the simulation and the overall procedures is illustrated in Figure 2.

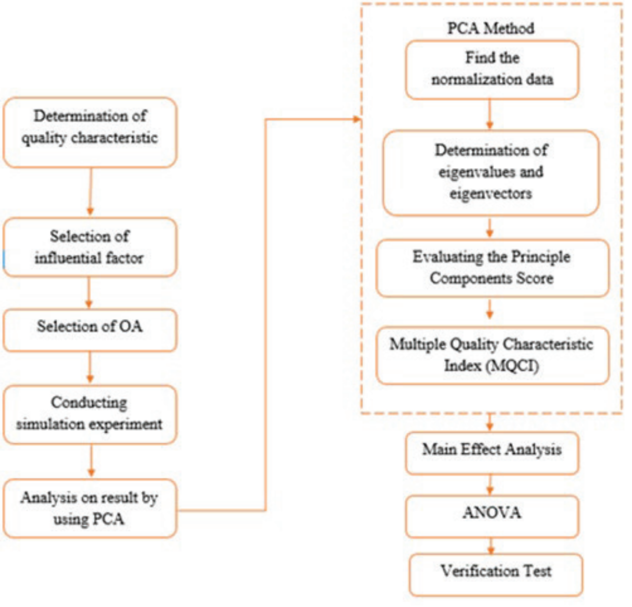

Figure 2: Overall procedures of Taguchi Method/PCA integration

2.1 Selection of Influential Factors

Several control factors were selected in this study including different gate types, size of micro gear, material selection as well as processing parameters. The processing parameters that will be considered in this work including filling pressure, injection time, injection pressure, cooling time and melting temperature. The selected control factors and their levels are shown in Table 1.

Table 1: Floating-point operations necessary to classify a sample

Column	Factor	Level 1	Level 2	Level 3
A	Gear size (mm)	5	6	7
B	Material	ABS	PA	PC
C	Gate type	Side	Diaphragm	Multiple pin
D	Melting temperature (°C)	200	240	260
E	Filling pressure (%)	60	80	100
F	Filling time (s)	0.05	0.1	0.15
G	Injection pressure (MPa)	130	150	170
H	Injection time (s)	0.05	0.1	0.2
I	Cooling time (s)	4	8	12

2.2 Selection of Orthogonal Array (OA)

There are nine factors in total with three levels each. Each three-level factor has two DOF (DOF= number of levels-1). The total DOF required was 18. The total of DOF of selected OA should be greater than or least equal to the total DOF of studied factors in the Taguchi method. Therefore, a L27 OA was selected in conducting the simulation and tabulated in Table 2.

Table 2: OA L27 (3^{13}) of simulation runs

Trial No	A	B	C	D	E	F	G	H	I
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2
5	1	2	2	2	2	2	2	3	3
6	1	2	2	2	3	3	3	1	1
7	1	3	3	3	1	1	1	3	3
8	1	3	3	3	2	2	2	1	1
9	1	3	3	3	3	3	3	2	2
10	2	1	2	3	1	2	3	1	2
11	2	1	2	3	2	3	1	2	3
12	2	1	2	3	3	1	2	3	1
13	2	2	3	1	1	2	3	2	3
14	2	2	3	1	2	3	1	3	1
15	2	2	3	1	3	1	2	1	2
16	2	3	1	2	1	2	3	3	1
17	2	3	1	2	2	3	1	1	2
18	2	3	1	2	3	1	2	2	3
19	3	1	3	2	1	3	2	1	3
20	3	1	3	2	2	1	3	2	1
21	3	1	3	2	3	2	1	3	2
22	3	2	1	3	1	3	2	2	1
23	3	2	1	3	2	1	3	3	2
24	3	2	1	3	3	2	1	1	3
25	3	3	2	1	1	3	2	3	2
26	3	3	2	1	2	1	3	1	3
27	3	3	2	1	3	2	1	2	1

2.3 Analysis on Results by PCA

To overcome the limitation of Taguchi method, the PCA is integrated with Taguchi method. By using PCA, a set of original responses is transformed into a set of uncorrelated components to find the optimal factor or level combination. The application of PCA involves a series of steps that are capable of solving the weakness of the standalone Taguchi method, which requires engineering judgement to handle multiple quality characteristics because the judgement of an engineer increases uncertainty during the decision making [14]. The procedures of implementing PCA in analyzing the results are as follows:

Step 1: Find the normalization data, to avoid discrimination of variables in calculation results

$$X'_i(j) = \frac{x_i(j) - \min x_i(j)}{\max x_i(j) - \min x_i(j)} \tag{1}$$

Step 2: Calculate the correlation coefficient array of the normalized response.

$$R = \frac{(Cov([x\text{^}']\_i(j)[,x\text{^}']\_i(l)))}{(\sigma\_(i(j)) \times \sigma\_(i(l)))} \tag{2}$$

where $j = 1,2...,n; l = 1,2....m$

Step 3: Determination of eigenvalues and eigenvectors. Eigenvalue is the original total variance while eigenvector is the list of coefficient of the original variables.

$$(R - \lambda_k I)(V_k) = 0 \tag{3}$$

where

$\sum \lambda_k = n; k = 1,,2,....,n.$
$V_k = \text{Eigen vector}; V = V_1, V_2 ..., n.$

Step 4: Evaluating the Principle Components (PC) Score. The PC scores can be obtained as linear combination of the original variable and the weighted.

$$Y_k = \sum x'_m(i) \bullet V_k \tag{4}$$

Step 5: Multiple Quality Characteristic Index (MQCI) to represent all responses of quality characteristic.

$$MQCI = \sum_{i=0}^{n} W_i \times Y_{ii} \tag{5}$$

3.0 RESULTS AND DISCUSSION

3.1 The Development of PCA

In the simulation, sink index, volumetric shrinkage and deflection are considered as quality characteristics. These quality characteristics are continuous and non-negative, and can be recognized as the smallest-the-better type. The results of these multiple quality characteristics are normalized to a unit value, ranging from 0 to 1 by using Equation (1). The normalization data for each quality characteristics is tabulated in Table 3.

Table 3: The normalization for each quality characteristic

Trial No	Sink index	Volumetric shrinkage	Deflection
1	0.192	0.042	0.035
2	0.158	0.048	0.027
3	0.000	0.000	0.010
4	0.223	0.667	0.625
5	0.238	0.678	0.620
6	0.221	0.674	0.617
7	1.000	0.349	0.000
8	0.534	0.451	0.111
9	0.443	0.451	0.102
10	0.968	0.203	0.464
11	0.947	0.268	0.411
12	0.306	0.161	0.416
13	0.306	0.984	0.172
14	0.296	0.922	0.172
15	0.317	0.980	0.172
16	0.334	0.218	0.062
17	0.371	0.496	0.080
18	0.357	1.124	0.092
19	0.623	0.270	0.145
20	0.714	0.258	0.138
21	0.623	0.228	0.098
22	0.208	1.000	0.215
23	0.378	0.806	0.214
24	0.317	0.987	0.214
25	0.614	0.226	0.706
26	0.614	0.474	1.000
27	0.351	0.303	0.803

Normalized data in Table 3 is then utilized to construct the variance and covariance matrix. The correlation coefficient matrix of the normalized data is further used in determining the eigenvalues and eigenvectors by adopting Equation (2) and Equation (3). Table 4 shows all the eigenvectors, eigenvalues and percentage of variability of each sink ink, volumetric shrinkage and deflection.

Table 4: Eigen analysis of the correlation matrix

Quality characteristics	Eigen vectors			Eigen values	Variability (%)
	PC1	PC2	PC3		
Sink Index	0.716	0.060	0.696	1.261	42.025
Volumetric Shrinkage	-0.662	0.375	0.649	1.016	33.856
Deflection	0.222	0.925	-0.308	0.724	24.119

In order to facilitate the optimization for this study, the total of PC scores or named as multiple quality characteristic indices (MQCI) are determined by utilizing the PC scores and explanatory total variance via linear combination of matrix as in Equation (4) and Equation (5). The results of MQCI are tabulated in Table 5. Note that MQCIs represent all the quality characteristics into 1 index, which in this case are sink index, volumetric shrinkage and deflection.

Table 5: Principal component scores and MQCI

Trial No	Sink index	Volumetric shrinkage	Deflection	MQCI
1	-0.001	-1.420	-1.247	-0.78
2	-0.116	-1.449	-1.321	-0.858
3	-0.486	-1.599	-1.832	-1.187
4	-0.662	1.309	-0.624	0.014
5	-0.646	1.307	-0.556	0.037
6	-0.689	1.289	-0.607	0.0004
7	1.666	-1.004	1.624	0.751
8	0.228	-0.620	0.405	-0.016
9	-0.039	-0.673	0.163	-0.204
10	2.245	0.415	0.723	1.258
11	2.013	0.301	0.851	1.153
12	0.402	0.046	-1.136	-0.089
13	-1.425	0.131	0.737	-0.376
14	-1.331	0.059	0.589	-0.397
15	-1.386	0.129	0.760	-0.355
16	0.078	-1.097	-0.544	-0.469
17	-0.351	-0.715	0.076	-0.371
18	-1.622	0.026	1.241	-0.373
19	0.867	-0.685	0.262	0.195
20	1.144	-0.701	0.498	0.363
21	0.911	-0.893	0.234	0.136
22	-1.700	0.273	0.448	-0.514
23	-0.834	0.093	0.543	-0.187
24	-1.365	0.281	0.725	-0.303
25	1.390	1.185	-0.489	0.867
26	1.141	2.470	-0.344	1.233
27	0.568	1.541	-1.179	0.476

3.2 Main Effects Analysis and Optimization of MQCI

For better understanding in identifying the optimal controlled factors, main effect analysis is exploited to examine the optimum performance of MQCI obtained in Table 5. Generally, main effect analysis is the effect of response experiment (dependent variable) on the averaging of controlled factors (independent variable) according to their levels. The mean response at each level of controlled factors is computed by averaging the performance values of each factor at different levels. The main effects of all the controlled factors on sink index, volumetric shrinkage and deflection, which in this case is indicated as MQCI is tabulated in Table 6.

Table 6: Main effect analysis on MQCI

Factors	Level 1	Level 2	Level 3	Max-min	Rank
A	-0.249	-0.002	0.251	0.5	2
B	0.021	-0.231	0.210	0.441	3
C	-0.560	0.549	0.010	1.109	1
D	-0.153	-0.051	0.205	0.358	5
E	0.161	0.106	-0.211	0.372	4
F	0.063	-0.012	-0.050	0.113	9
G	0.075	-0.123	0.047	0.198	7
H	0.095	-0.035	-0.059	0.154	8
I	-0.158	0.033	0.125	0.283	6

According to Table 6, the ranking of influential factor towards the MQCI can be obtained by evaluating the difference values of maximum and minimum values. The result of ranking 1st to 9th of influence factor goes to gate type, gear size, material selection, filling pressure, melting temperature, cooling time, injection pressure, injection time, and filling time accordingly. For better interpretation of the main effects analysis, the results in Table 6 can be converted into a graphical display as shown in Figure 3.

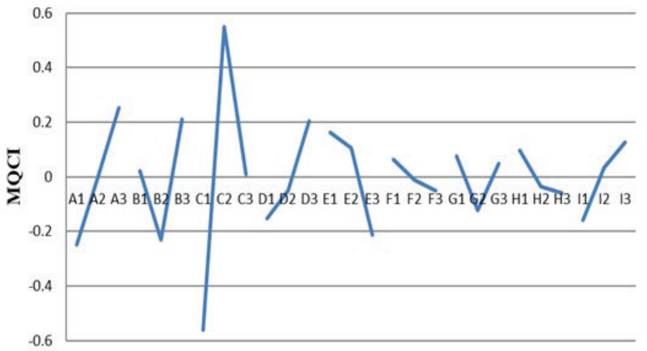

Figure 3: Main effect analysis plot

Referring to Figure 3, it is clearly shown that the multiple quality characteristics which in this case indicated by MQCI of the simulated micro spur gear are greatly influenced by the variation in gate types, gear sizes, material selection as well as adjustments of the processing parameters. There are three different plastic materials are assigned as material for the simulated micro gear which are Acrylonitrile Butadiene Styrene (ABS), Polyamide (PA) and Polycarbonates (PC). Meanwhile for gate types, side gate, diaphragm gate and multiple pin gate are being selected to examine the impact of different gate type on sink index, volumetric shrinkage and deflection of the micro gear.

The best combination of factors and levels could easily be obtained from the main effects analysis by selecting the level of each factor with the highest MQCI value. As a result, the optimal factors which statistically result in the minimum sink index, volumetric shrinkage and deflection for the simulated micro spur gear, are predicted to be A3B3C2D3E1F1G1H1I3. As seen in Figure 3, the optimal factors represent a gear size of 7mm, material of polycarbonate (PC), gate type of diaphragm, 260 ºC melting temperature, 60% filling pressure, 0.05 s filling time, 130 MPa injection pressure, 0.05 s injection time and 12 s cooling time.

3.3 Analysis of Variance (ANOVA)

The Taguchi method not only can generate the response plots to illustrate the quality changes caused by varying each factor, but it can also perform the ANOVA to enable engineers to quantitatively estimate the relative contribution of each factor to the overall measured response. As there are three quality characteristics including sink index, volumetric shrinkage and deflection involved in this study, the ANOVA is performed for multiple quality characteristics towards the MQCI. ANOVA is analyzed by computing the quantities degrees of freedom, (f), sum of squares (S), variance (V), F-ratio and percentage contribution of the MQCI (%) and listed in Table 7.

Table 7: ANOVA of MQCI

Column	Factor	f	S	V	F-ratio	%
A	Gear size	2	1.131	0.565	7.609	10.994
B	Material	2	0.883	0.441	5.943	8.588
C	Gate type	2	5.554	2.777	37.350	53.968
D	Melting temperature	2	0.614	0.307	4.133	5.972
E	Filling pressure	2	0.739	0.369	4.969	7.181
F	Filling time	2	0.061	0.030	0.412	0.596
G	Injection pressure	2	0.207	0.103	1.397	2.018
H	Injection time	2	0.125	0.062	0.842	1.217
I	Cooling time	2	0.378	0.189	2.547	3.681
All Other / Error		8	0.594	0.074	1.000	5.779
Total		26	10.292	0.395		100

In determining the relative contribution of each factor in ANOVA, the value of F-ratio of the factors which are greater than the F-table of specific confidence level is statistically considered as significant [15]. In this study, for level of significance (90% confidence), the obtained result $F_{.10}(2,8) = 3.1131$. Returning to Table 7, out of nine factors, only five factors, including gate type, gear size, material, filling pressure and melting temperature are considered as significant as their F-ratios are greater than the threshold values of $F_{.10}$ (90% confidence level).

4.0 CONCLUSION

As indicated from the results of optimization of simulated plastic micro gear, it can be viewed that the adoption of integration of the Taguchi method and PCA is an effective approach in optimizing the influential factors related to multi quality characteristics where in this case is sink index, volumetric shrinkage and deflection area. The findings showed that the different plastic material selection for micro gear, types of gate, size of gear as well as processing parameters have an impact on the quality of injected micro gear where in this case are sink index, volumetric shrinkage and deflection. From ANOVA, the results showed that the most significant factor is gate type where in this case is diaphragm gate with the percentage of contribution of 53.968%.

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