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Optimization of Molding Parameters for a Micro Gear with Taguchi Method

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Abstract. Nowadays, micro injection molding became one of the technologies for micro manufacture. It is widely used as a cost-effective replication method for mass production of plastic parts. However, one of the challenges for micro molding is the shrinkage which will deteriorate the quality of the micro parts molded. The way to control and minimize the shrinkage is by mean of optimizing the molding parameters. Optimizing process parameter problems are routinely performed in the manufacturing industry, particularly in setting the final optimal process parameters. Final optimal process parameter setting is recognized as one of the most important steps in injection molding for improving the quality of molded products. In this study, Taguchi method was implemented in finding the optimal micro injection molding condition for minimum shrinkage of a micro gear in micro molding experiment. Analysis of Variance (ANOVA) was carried out to determine the most influential factor that contributes towards the shrinkage quality of micro gear. The influential factors that affecting shrinkage are packing time with a contribution of 32.47% and injection speed with a contribution of 22.34%.

1. Introduction

In recent years, there are more and more demands about small and even micro scale parts in many industrial fields. Thus, this trend towards miniaturization makes the micro system technologies of growing importance. Micro injection molding is considered as one of the micro system technologies, it has the capability for mass production with relatively low production cost. Furthermore, micro injection molding can be designated to the fabrication of components with micro-features or components with volumes in the range of milligrams. Loh et al. [1] used micro injection molding to manufacture a 10 teeth micro gear with a module of 0.08, outer diameter of 1 mm and length of 1 mm. In another study, Hakimian and Sulong [2] applied Taguchi method to analyze warpage and shrinkage properties of polymer composites micro gears. Their results indicated that the minimum values for warpage is 0.0051 mm and shrinkage is 2.2886%. The results also indicated that PPE/PS is the best polymer composite by shrinkage analysis while PC/ABS is the best in the warpage analysis.

Optimal process parameter setting is considered as one of the most important steps in injection molding for improving the quality of molded products. Thus, many optimization methods have been proposed and implemented by many researchers. Taguchi and artificial neural network methods are two of the typical optimal methods. Some researchers have been performed to optimize the levels of process parameters based on Taguchi's orthogonal array experiment. In addition, the effect of process parameters on the warpage and shrinkage can be presented by using a statically analysis of variance (ANOVA) Mirigul Altan [3] combined Taguchi, ANOVA and neural network methods together to reduce shrinkage defects in injection molding. This study found out the optimal parameter combination is 260^{0}C for melt temperature, 60 MPa for injection pressure, 50 MPa for packing pressure, and 15 s for packing time, and the minimum shrinkage for PP part is 0.937% and 1.224% for PS part. Zhao et al. [4] successfully fabricated highly oriented self-reinforced Polyoxymethylene (POM) through solid phase hot stretching technology. POM material can be used as many high-performance engineering parts namely; small gear wheels, ski bindings, ball bearings, knife handles, fasteners, lock systems, and model rocket launch buttons. In this research, POM will be used for the molding of a micro gear.

This paper attempts to describe the optimization of the micro injection molding process parameters for optimizing shrinkage performance of a POM micro gear. In this paper, the process parameters such as mold temperature, injection speed, packing pressure, packing time, packing speed and melt temperature will be included to find the best molding quality of the micro gear. Taguchi method will be implemented to find the optimal processing parameters in micro injection molding experiments.

2. Literature references

Micro injection molding can be defined as one of the key technologies for micro manufacturing because of its mass production capability and relatively low production cost. The process design of micro injection molding involves the determination of many processing parameters like pressure (injection, holding, and melt), temperature (coolant, nozzle, barrel, melt and mold), time (fill, holding, cooling, and cycle), clamping force, injection speed, injection stroke, etc. Therefore, process parameters play an important role for fabricating product in micro injection molding process. Yu et al. [5] indicated that mold temperature is the most crucial factor that controls the success of the complete filling. To make the melted filling easier, they applied an infrared heating system to raise the mold cavity temperature before and during the filling process. Ong et al. [6] analyzed the molding parameters affecting the mass of micro-parts using a design of experiment methodology. Mold temperature was the most significant factor in this study. Besides that, high mold temperature, high injection rate, and high injection pressure are recommended for the filling process.

Plastic micro injection molded gears have been widely applied to replace those expensive micro-machined metal gears in drug delivery system, aerospace, automotive parts, and many other micro-electro-mechanical devices. Huang et al. [7] applied the robust parameters design to the fabrication of a micro gear and found that the significant parameters for diameter dimensions are mold temperature, injection speed and holding pressure whereas for tooth thickness are holding pressure, cooling time and mold temperature. Shrinkage, residual stresses, and warpage are connected in a complicated way. Nevertheless, just the shrinkage of the plastic part, the most important section in designing and fabricating micro parts, is going to be investigated in this paper.

Some researchers have used various optimal methods such as Genetic algorithm, neural network and Taguchi methods to lessen molding part shrinkage rates. Shen et al. [8] applied a combination of the neural network and genetic algorithm methods in the injection molding process to improve the quality index of the volumetric shrinkage. Oktem et al. [9] employed the Taguchi method to calculate the optimum levels of process parameters on thin-shell part, the results showed the warpage and shrinkage are decreases about 2.17% and 0.7%.

3. Experiment

3.1 Design of micro gear

The material used in this paper is a semi-crystalline Polyoxymethylene (POM). POM has been widely used in micro injection molding studies because of its processing characteristics, such as high mechanical strength and rigidity, excellent dimensional stability, natural lubricity, fatigue endurance, high resistance to repeated impacts, toughness at low temperature, and excellent resistance to moisture. Some of POM's properties are listed in table 1. The gear design and the mold system for this study are shown in figure 1 and 2.

Table 1. Properties parameter for POM.

Parameter	Values
Mass density (g/cm^3)	1410
Melt temperature (^{o}C)	175
Crystallization temperature (^{o}C)	148
Poison ratio	0.35

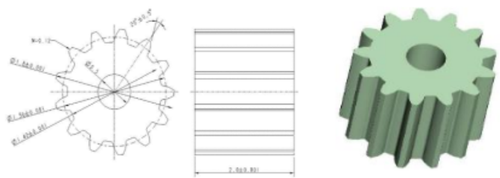

Figure 1. Design of the micro gear

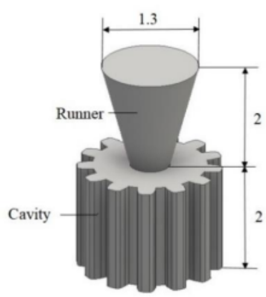

Figure 2. Design mold system

3.2 Taguchi method

There are a lot of processing parameters that influence molding part quality particularly shrinkage. These parameters are melt temperature, mold temperature, packing time, packing pressure, cooling time, injection pressure, injection speed, and injection time. In this research, the packing pressure, packing time, injection speed, melt temperature and mold temperature, are examined to minimize the shrinkage on the dimensions of micro gear. These five parameters are chosen as control factors in the Taguchi experiment. The array of the mold temperature (A) is chosen to be 70^{o}C - 90^{o}C, the injection speed (B) is selected in the range between of 100-200 mm/sec, packing pressure (C) is selected in the range between of 170-210 MPa, the packing time (D) and melt temperature (E) are chosen to be in the range of 2.6-3.6 sec and 180^{o}C - 200^{o}C, respectively. Each of the range of the control factors is divided into 3 levels, so an L_{18} Orthogonal Array (OA) is appropriated for this experiment and will be used in this study, and the L_{18} Orthogonal Array layout in table 2 shows the values of the control factors for each experimental run.

4. Result and discussion

After molding of the micro gears, measurement of dimensions of the part at three locations (outside diameter, inside diameter, and whole depth) shown in figure 2 was carried out. Three micro gear specimens were measured for each experimental run. The relative shrinkage of selected characteristics was calculated with the following eq. 1

$$S_L = \frac{(D_m - D_p)}{D_m} x100\% \qquad (1)$$

Where S_L indicates the linear shrinkage, D_m indicates the dimension of mold, and D_p indicates the dimension of the part, and the linear shrinkages at the 3 locations for each run were listed in table 2

Table 2. Original dimension of the mold.

	Outside diameter	Inside diameter	Whole depth
Mold	2.34	0.64	0.25

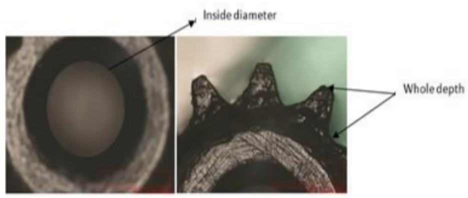

Figure 3. The measured dimension

Table 3. The L_{18} orthogonal array and the result of taguchi experiment.

Exp.	A	B	C	D	E	Shrinkage (S_L) y_1	y_2	y_3	Average Shrinkage (S_L)	y^2 (10^{-3})	S/N
1	70	100	170	2.6	180	0.095	0.098	0.097	0.097	9.3	20.294
2	70	150	190	3.1	190	0.061	0.065	0.066	0.064	4.1	23.871
3	70	200	210	3.6	200	0.060	0.063	0.065	0.063	3.9	24.055
4	80	100	170	3.1	190	0.078	0.077	0.076	0.077	5.9	22.270
5	80	150	190	3.6	200	0.063	0.060	0.060	0.061	3.7	24.291
6	80	200	210	2.6	180	0.075	0.071	0.077	0.074	5.5	22.571
7	90	100	190	2.6	200	0.088	0.085	0.080	0.084	7.1	21.473
8	90	150	210	3.1	180	0.064	0.060	0.061	0.062	3.8	24.196
9	90	200	170	3.6	190	0.066	0.069	0.070	0.068	4.7	23.305
10	70	100	210	3.6	190	0.069	0.072	0.066	0.069	4.8	23.218
11	70	150	170	2.6	200	0.068	0.074	0.075	0.072	5.2	22.805
12	70	200	190	3.1	180	0.069	0.077	0.078	0.075	5.6	22.525
13	80	100	190	3.6	180	0.059	0.065	0.060	0.061	3.8	24.238
14	80	150	210	2.6	190	0.067	0.066	0.065	0.066	4.4	23.608
15	80	200	170	3.1	200	0.067	0.070	0.071	0.069	4.8	23.179
16	90	100	210	3.1	200	0.073	0.074	0.072	0.073	5.3	22.733
17	90	150	170	3.6	180	0.075	0.075	0.075	0.075	5.6	22.499
18	90	200	190	2.6	190	0.073	0.076	0.076	0.075	5.6	22.497

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From the response graph figure 4, the best parameter combination is able to be calculated by choosing the level with the highest value of each factor, and that is A2B2C3D3E2 which corresponds to the mold temperature of 80ºC, injection speed 300 mm/s, packing speed 20 mm/s, packing time 1 second, and melt temperature 190ºC. The interaction between factors ignored.

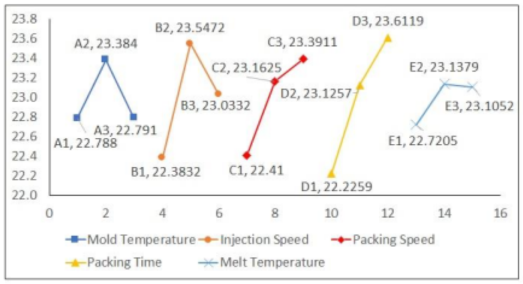

Figure 4. Response graph S/N

The micro gear molded with the optimal parameter combination results in a shrinkage of 0.06. The micro gears fabricated by using optimal parameters are shown in figure 5.

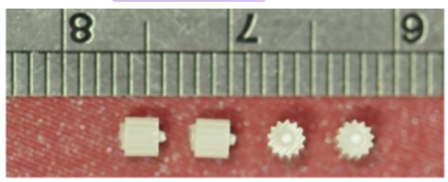

Figure 5. Different views of the micro gear molded

In this part, the aim of using the Analysis of Variance (ANOVA) is also to determine the significance of process parameters on shrinkage in fabricating micro gear process. Based on the calculation of S/N ratio, ANOVA value can be obtained. The most significant parameter was determined by calculating the percentages contribution. Based on the data in Table 4, the ANOVA method was computed with some quantities such as degrees of freedom, squares sums, F-ratio, variance, square pure sum and contribution of percentage.

Table 4. Analysis of variance for shrinkage.

Source of variance	The degree of freedom (DOF) (*f*)	Sum of squares (S)	Variance (V)	F-ratio (F)	Percentage contribution P (%)
Mold temperature	2	1.413	0.7065	1.629	7.732
Injection speed	2	4.0833	2.0416	4.708	22.34
Packing speed	2	3.1624	1.5812	3.646	17.3
Packing time	2	5.934	2.967	6.842	32.47
Mold temperature	2	0.6465	0.3232	0.745	3.537
Pooled error	7	3.0353	0.4336		16.6097
Total	17	18.274			100

These results show that the packing time contributes the most by 32.47% and this is followed by the injection speed contributes 22.34%, the packing speed of 17.3%, mold temperature by 7.732%, and melting temperature of 3.537 % as the influence factor for shrinkage defect. This proves that packing time, injection speed, packing speed are the most significant parameters contribute to improving shrinkage in the process while mold temperature and melt temperature only have small effects towards the shrinkage of the parts.

5. Conclusion

In summary, shrinkage occurs in all micro molded plastic parts for many reasons. However, the question is how these defects can be reduced and which parameters are dominant in this process. Therefore, it is significant to understand and determine the cause and effect of these defects. Moreover, it will be improved completely by optimizing some process parameters using the Taguchi method. The current studies have obtained considerable results to identify the relationship between them. Packing pressure, melt temperature, packing time, injection speed, and packing speed are some of the major molding parameters influence the part shrinkage.

During the fabricating process, the dimension of micro gear is very small, therefore, many defects such as weld line, warping, bubbles, sink marks are very difficult to detect. Besides, measuring the dimension of micro gear was not get accurate figures, thus the error happens during the measuring process. The experimental results support the proposed approach which not only enhances the stability of the entire micro injection molding process but also improves the quality characteristics and shrinkage.

Acknowledgment
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