COMPLETE ROBUSTNESS FOR NON-UNIFORM SHRINKAGE OF THE PLASTIC INJECTION MOLDING PROCESS

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ABSTRACT

The plastic industry is one of the most rapidly growing industries. The injection molding process is one of the main processes, accounting for approximately 32 percent by weight of plastic produced [3]. In this process, shrinkage of the molded parts is one of the most serious problems because it is not uniform over time and dimensional range. This leads to parts' quality problems and iterations of mold modification in order to arrive at the required dimensions. This paper presents a design of an experiment to reduce non-uniform shrinkage and make shrinkage less sensitive to uncontrollable factors such as environmental temperature. Twenty-seven runs of experiments were performed, allowing sufficient time to let the machine stabilize between runs. The results were anlyzed by employing signal-to-noise ratio (S/N ratio) as a criterion to search for uniform shrinkage condition. The optimal conditioin from calculation was verified by confirmation test. In addition, a process parameter that is highly associated with shrinkage was suggested in case of adjusting molded parts dimensions within a small range.

INTRODUCTION

Shrinkage is defined as the difference between corresponding linear dimensions of the mold and the molded piece [5]. These measurements are made at room temperature. Shrinkage varies considerably depending on types of plastic, part geometry, process conditions, machinery, etc. Usually, information about an approximate amount of shrinkage can be obtained from the material manufacturers. This information is based on a test bar, normally 0.125 inch thick, which is molded according to ASTM standards.

However, the actual process conditions are often different from the standard conditions, thus causing non-uniform shrinkage which differs from manufacturers' specifications. The calculated shrinkage in theory [1] dictates the allowances to be provided in the mold. But except for simple shapes, more often the critical key dimension of the part will not be as predicted by theory, especially if the item is long and/or complex, or if it requires tight tolerance [4].

In addition to difficulty in mold development, non-uniform shrinkage also causes the quality problem because, between injections, shrinkage at the same position is not uniform. As a result, we have to spend time and costs to inspect molded parts. This problem becomes more serious in the case of precision parts.

MODEL OF THE PROBLEM

The injection molding process involves a transformation from mold dimensions to injected part dimensions. As represented in Fig. 1, mold dimensions are the input signals of this process and injected part dimensions are the output signals. The mold and injected part dimensions are related by an unknown function. The injection molding process is also suceptible to uncontrollable factors or noise such as changes in environmental temperature and humidity, uneven temperature distribution in the mold, and variation of raw material properties. This noise usually distorts the functionability of the process. This process can be improved by operating at a new setting level of process parameters, such as injection pressure, that makes the process less sensitive to noise.

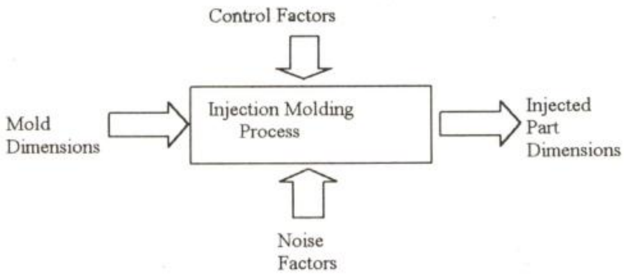

Fig. 1 Injection molding model.

For this engineering problem solving, it is not necessary to develop the exact relationship among all factors. The important task is to identify an appropriate setting value of each control parameter to make the process close to the ideal function, as illustrated by the Equation (1).

$$Y= \beta.M \qquad (1)$$

where "Y" is an injected part dimension, "M" is the corresponding mold dimension, and "β" is the constant factor that relates mold and part dimension. It is obvious that the ideal function does not have any noise effect. In other words, it is insensitive to noise. The effects of noise usually appear in two types of variations from ideal function, as demonstrated is Fig. 2.

1. The variation between injections: From one injection to another, difference in environmental conditions such as temperature and humidity, may affect the process; as a result, injected part dimensions are not consistent with the corresponding mold dimensions. For example, with the mold dimension M1, the part dimension in the first injection is y_{11}, but the one in the second injection is y_{12}.

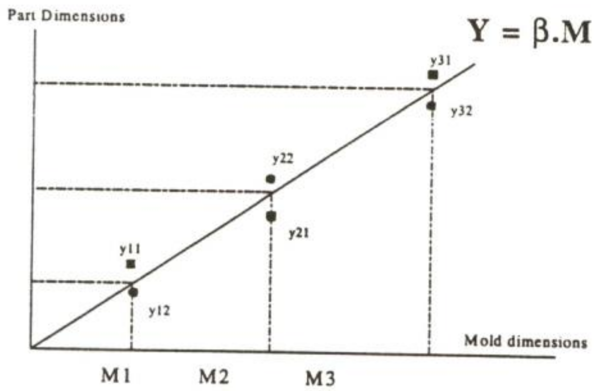

Fig. 2 Deviation from the ideal function [2].

2. The variation of β coefficient; From one dimension to another, the β coefficient may not be exactly the same. Thus, the actual output deviates from the ideal output. For example, the average of y from the mold dimension M1 is $\beta_1 M1$, but one from the mold dimension M2 is $\beta_2 M2$.

To improve functional robustness to noise, the Taguchi parameter design is employed to locate the set of optimal setting values for all control parameters. The Taguchi Method is employed to search for the optimum condition. It is the most powerful and cost-effective approach in engineering optimization to find out the best alternative without having to evaluate all of the possible alternatives explicitly. The method helps to reach the better quality at low cost. Taguchi optimization can be carried out by experimentation based on the orthogonal arrays and Signal-to-Noises (S/N) ratio criterion.

EXPERIMENTAL PROCEDURES

Parameter & Level Selection

The selection of 13 parameters that were used to control the process was done with the help of the experts from Mountain View Fabricating. These parameters were felt to be independent and significant to the process. They are shown in Table 1.

Table 1 Parameters and Levels

Parameters	Description	Levels		
		1	2	3
A	Cavity temperature (C)	65	38	93
B	Barrel temperature 1 (C)	282	271	293
C	Barrel temperature 2 (C)	289	277	299
D	Nozzle temperature (%of parameter C)	65	55	75
E	Injection pressure ($x10^6 N/m^2$)	6.16	4.23	8.10
F	Back pressure ($x10^6 N/m^2$)	0.35	0	0.88
G	Hold pressure ($x10^6 N/m^2$)	4.93	3.88	7.40
H	Injection time 1st stage (s)	2.0	1.5	3.0
I	Injection time 2nd stage (s)	6	8	10
J	Cooling time (s)	28	23	32
K	Mold opening time (s)	.75	.5	1.0
L	Injection speed (in./s)	8.8	2.0	5.8
M	Screw speed (in./s)	3.1	2.0	5.0

The Response

The mold in this experiment was composed of three cavities. The selected cavity dimensions are shown in Table 2. During the stable running stage of the selected machine, two injections were taken as samples for measurement in order to detect impact of noise. Due to three cavities, each injection produced three parts, numbered 1, 2 and 3. The average value of three molded parts was used to represent that mold dimension.

Table 2 Mold Cavity Dimensions

Dimension	M1 (mm)	M2 (mm)	M3 (mm)
Cavity 1	6.68	49.66	90.22
Cavity 2	6.55	49.68	90.55
Cavity 3	6.63	49.66	90.27
Average	6.62	49.66	90.35

These dimensions are orthogonal and different in size because we need to make shrinkage robust to uncontrollable factors or noise for all possible directions and dimensions of the molded parts within an experimental rage. Therefore, the result can be applied for any future products within experimental range.

Experiment Pattern Selection

There are 13 process parameters at three levels, so the total number of combinations is 3^{13} or 1,594,323 runs which are impossible to experiment on all combinations. We need to find the smallest number of runs that is able to present the process phenomena. However, the minimum number of runs has to be more than degrees of freedom of the studied system. The degrees of freedom for this can be computed by using Equation 2.

$$df = \sum_i (l_i - 1) \qquad (2)$$

where df is degrees of freedom and l_i is the number of levels of parameter i. As a result, the degrees of freedom in this parameter set are 26. Therefore, the orthogonal array L_{27} pattern was employed for this experiment.

Signal-to-Noise Ratio Calculation for Each Run

In each run, we took two samples from two injections and in each sample, we measured three dimensions. The signal-to-noise ratio can be computed as demonstrated in Equation 3.

$$SN = 10\log\left(\frac{\beta^2}{\sigma^2}\right) \qquad (3)$$

$$\beta = \frac{\sum_{j=1}^{3}\sum_{i=1}^{2} y_{ij}\ M_j}{\sum_{j=1}^{3} M_j^2}$$

$$\sigma^2 = \frac{\sum_{j=1}^{3}\sum_{i=1}^{2} y_{ij}\ (y_{ij} - \beta M_j)^2}{ij\text{-}1}$$

where β = transformation coefficient

σ^2 = impact of noise or variation from ideal function

y_{ij} = injection i dimension j of the molded part

M_j = dimension j of the mold cavity

i = injection no.

j = dimension no.

OPTIMAL SETTING VALUE

After calculating S/N ratio of each run, the mean S/N ratio associated with each level of a process parameter is computed by averaging the S/N ratios of the parameter at that level. The optimal setting level of each parameter is the level that yields maximum average S/N ratio. Table 3 shows average S/N ratios and optimal level of each parameter.

Table 3 Average S/N Ratios

Parameter	Level 1	Level 2	Level 3	Optimal Condition
A	37.40	41.32	41.07	A2-38C
B	41.31	37.35	41.12	B1-282C
C	41.36	37.20	41.42	C3-299C
D	41.25	37.34	41.20	D1-65%
E	41.16	37.49	41.15	E1-6.16 MN/m^2
F	41.33	37.29	41.18	F1-0.35 MN/m^2
G	40.97	37.04	41.79	G3-8.10 MN/m^2
H	41.12	41.12	37.46	H2-1.5 sec
I	41.15	41.39	37.25	I2-8.0 sec
J	41.19	41.34	37.27	J2-23 sec
K	37.34	41.14	41.31	K3-1.0 sec
L	37.35	41.15	41.30	L3-5.8i n./s
M	37.31	41.30	41.18	M2-2.0 in./s

FINE ADJUSTING PARAMETER

Fine adjusting parameter is the most influential parameter on β coefficient. It is employed in the case that there is a slight error on a built mold. Another case is when the raw material properties is slightly different from the current one due to supplier change. Engineers can use this parameter to adjust the part's size to desired dimensions. The analysis is designed to investigate the adjustment capability of each parameter, so the analysis have to be done parameter by parameter. Actually, orthogonal array L_{27} is one part of all possible combinations. Thus, the impact of each parameter will confound with some interactions. Fortunately, if we consider only one parameter and average all measurements associated with the parameter's levels, all interactions will cancel each other. For example, if we average measurements associated with parameter A at level 1, all interactions (e.g. A*B, A*B*C) associated with A at level 1 will be zero. As a result, the analysis layout can be simplified to be two-way

Table 4 Layout for Fine Adjusting Parameter

Level	Injection #	M1	M2	M3
1	1	y_{111}	y_{121}	y_{131}
	2	y_{112}	y_{122}	y_{132}
2	1	y_{211}	y_{221}	y_{231}
	2	y_{212}	y_{222}	y_{232}
3	1	y_{311}	y_{321}	y_{331}
	2	y_{312}	y_{322}	y_{332}

layout as shown in Table 4.

The adjusting capability can be measured by F statistics because it is a ratio of parameter effect to noise effect. The most appropriate fine adjusting parameter is the parameter that yields highest F statistic. From Table 5, hold pressure should be used as the fine adjusting parameter because its changing has highest effect comparing to effect of noise.

Table 5 F Statistics of Process parameter

Process Parameter	F statistics
A : Cavity temperature	0.585
B : Barrel temperature 1	1.243
C : Barrel temperature 2	0.267
D : Nozzle temperature	0.824
E : Injection Pressure	0.832
F : Back pressure	0.644
G : Hold pressure	**4.915**
H : Injection time 1st stage	1.796
I : Injection time 2nd stage	0.538
J : Cooling time	0.747
K : Mold opening time	0.718
L : Injection speed	0.648
M : Screw speed	0.902

CONFIRMATION TEST

The confirmation test is used to verify that the optimal condition based on S/N ratio is better than the normal condition. The result is presented in Table 6.

Table 6 The Confirmation Test

List	Normal[A]	Optimal[B]	Improvement
S/N ratio	40.87 dB	44.07 dB	3.2 dB
β coefficient	0.998952	0.999831	0.09%
Difference between shots			
by average (mm)	0.00559	0.00078	85.57%
by variance (mm^2)	1.68e-4	2.79e-5	83.40%
Clearance between mold and part			
by average (mm)	0.126	0.0677	46.39%
by variance (mm^2)	0.0358	0.0179	50.02%

[A] Normal condition : A_1, B_1, C_1, D_1, E_1, F_1, G_1, H_1, I_1, J_1, K_1, L_1, M_1

[B] Optimal condition : A_2, B_1, C_3, D_1, E_1, F_1, G_3, H_2, I_2, J_2, K_3, L_3, M_2

CONCLUSION

Thirteen process parameters, three levels for each parameter, were investigated by using Taguchi-based design of experiments. The number of runs was reduced from 1,594,323 runs down to 27 runs. The objective of this experiment is to try to make shrinkage of the molded parts uniform over experimental range, dimensions, and time. From the result, the dimensional variation between shots was improved 83.40 %, and the uniformity of the clearance between mold and part was improved 50.02%. In addition, the analysis indicated that hold pressure is the most appropriate parameter used for dimensional fine adjustment of the molded parts.

In the future, a study of multi-response system is recommended because the number of quality characteristics may not be just only one, shrinkage in this case. Model of the system should integrate many responses and their interactions to locate a suitable condition for many requirements.

ACKNOWLEDGMENT

Thank you to the management and staff of Mountain View Fabricating, Inc., Missouri, USA for their support and allowing me to conduct this experiment at their facilities. Thanks to production department for operating the machine and to CMM department for their precise measurements.

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