20070213

ILL

ILL #: 27765536

(8)

ODYSSEY ENABLED

20070213

Borrower: IRU

Call #: TS200 .J64 Online

Lending String: *AZS,AZS,UBY,UND,UMR

Location: ONLINE ACCESS ONLINE ACCESS

Patron: Valles-Rosales, Delia J.

TN.#: 287181

Arizona State University Interlibrary Loan

Journal Title: Journal of materials processing technology.

Article Author:

Article Title: Park, K; Design of experiment considering two-way interactions and its application to injection molding processes with numerical analysis

Volume: 146
Issue: 2
Month/Year: 2004
Pages: 221-27

Shipping Address:
New Mexico State University Library
ZUHL LIBRARY - Interlibrary Loan
1305 Frenger Mall
Box 30006, Dept 3475
Las Cruces, NM 88003-8006

Fax: (505) 646-4335

Pulled by ________ **(Initials)**

Scanned by ________ **(Initials)**

Reason Not Filled (check one):

☐ NOS ☐ NFAC ☐ NONCIRC

☐ MISSING FROM VOL ☐ TOO LONG

☐ OTHER ________

LENDER:
Arizona State University Library
Interlibrary Loan
Cady Mall
Tempe, AZ 85287-1006
(480) 965-3282
OCLC: AZS (Odyssey enabled)
Ariel: 129.219.244.28
ill@asu.edu

ARIEL INFORMATION:

Ariel Address: 128.123.193.167

Enter Ariel Address Manually if unable to scan.
If Ariel address blank, send via US Mail.

ELSEVIER

Journal of Materials Processing Technology 146 (2004) 221–227

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Design of experiment considering two-way interactions and its application to injection molding processes with numerical analysis

Keun Park [a,*], Jong-Ho Ahn [b]

[a] School of Mechanical Design and Automation Engineering, Institute of Precision Machinery Technology, Seoul National University of Technology, 172 Gongneung2-dong, Nowon-Gu, Seoul, South Korea

[b] Manufacturing Technology Institute, Samsung Electro-Mechanics Co., Suwon, Kyunggi-Do, South Korea

Received 12 March 2002; received in revised form 28 March 2003; accepted 24 October 2003

Abstract

The optimal design for injection molding processes is sought by using the design of experiment (DOE) and numerical analysis. DOE is designed so as to consider two-way interactions, and have been applied progressively for both mold and process designs. Numerical analyses have been carried out as DOEs for mold parameters such as runner specifications and cooling channel configurations. In order to determine optimal process parameters, experiments have been performed for various process conditions with the DOE scheduling. As a result, the quality and productivity of the product have been improved, and the proposed approach can be successfully applied to the industrial injection molding process of precision electronics parts.

Keywords: Injection molding; Numerical analysis; Design of experiment (DOE); Two-way interaction

1. Introduction

Injection molding processes faced increasing requirements for higher quality and lower cost. From the viewpoint of mold design, there are numerous parameters which affect the quality and productivity of products, such as gate size and location, runner designs, design of cooling channels, injection pressure, injection temperature, cooling time, etc. These parameters also affect product quality in mutual interactions with each other as well as with separate factors. The effects of combinations of these parameters are quite difficult to analyze since they require numerous case studies as well as much time and cost.

In order to reduce such efforts and expenses, computer simulations for injection molding processes have been utilized since the early 1970s [1]. Computer aided engineering (CAE) analysis has supported useful research in the design of parts, molds, and molding processes with better efficiency [2,3]. However, considering the effects of such a large number of parameters even if computer simulations are utilized, tremendous efforts are still needed to find optimal molding process conditions. Thus, an efficient strategy for CAE analyses is required and the related results should be analyzed in a systematic manner.

Design of experiment (DOE) has been a very useful tool to design and analyze complicated industrial design problems. It helps us to understand process characteristics and to investigate how inputs affect responses based on statistical backgrounds. In addition, it has been used to systematically determine the optimal process parameters with fewer testing trials. The Taguchi approach is a DOE method that has been widely used in industrial robust design procedures. Several studies have been made on design of injection molding processes using the Taguchi approach [4–6]. Though this approach can identify the main effects of separate design factors, it is limited in that interactions among those factors cannot be considered effectively.

In general, there exist interactions among injection molding factors. Thus related experiments must be designed to consider interaction effects appropriately. The present work concerns a DOE approach based on factorial design for the proper consideration of interactions. This approach is then applied to determine the optimal conditions for the injection molding process of a deflection yoke. The deflection yoke controls the direction of electron beams discharged on television monitor screens. The quality of a monitor mainly depends on the shape and density of coils wound around the coil separator of the deflection yoke. The shape of coils

* Corresponding author. Tel.: +82-2-970-6358; fax: +82-2-974-8270.
E-mail address: kpark@snut.ac.kr (K. Park).

0924-0136/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2003.10.020

also relies on the precision of the coil separator, which is fabricated by injection molding. The design of the injection molding process is thus very important for the quality of the final products.

The optimal design for the injection molding process is developed using the DOE approach and finite element analysis. All the experiments are designed to be able to consider two-way interactions among various factors. The DOE approaches are applied progressively, such as DOE for mold design and DOE for process design. Finite element analyses are carried out as a numerical experiment of mold design. C-MOLD [7] is used for the analysis of the injection molding processes. In order to determine optimal process parameters, experiments are performed for various process conditions with design scheduling and statistical analysis.

2. Experimental design considering two-way interactions

Recently, the DOE procedure has been used to systematically investigate process variables or product variables that influence the quality of products. It is possible to identify the process conditions and product components that influence product quality and costs, which in turn enhance the product manufacturability, quality, reliability, and productivity. The DOE procedure consists of the following four steps [8]:

- *Planning*: definition of the problem and the objective, and development of an experimental plan.
- *Screening*: reduction of the number of variables by identifying the key variables that affect product quality.
- *Optimization*: determination of the optimal values for various experimental factors.
- *Verification*: performing a follow-up experiment at the predicted best processing conditions to confirm the optimization results.

The DOE approach can be divided into a full factorial design and a fractional factorial design. The full factorial design has the advantages that all kinds of main effects and interactions can be considered. However, since all combinations are to be tested, the number of experiments (N_{full}) increases exponentially as follows:

$$N_{\text{full}} = m(n_l)^k \quad (1)$$

where k is the number of factors to be investigated, n_l the experiment level, and m the number of replicates. Thus the number of experiments increases considerably when there are numerous input factors.

If higher order interactions are negligible, it is possible to use a fraction of the full factorial. It is generally recognized that three-way and higher interactions are so rare as to be negligible and can be thus ignored. The fractional factorial experiment is usually designed to be able to consider main effects and two-way interactions. It is efficiently used in the screening DOE procedures when there are a large number of factors. The number of experiments required ($N_{\text{fractional}}$) is then reduced as follows:

Table 1
Available factorial design with resolution [9]

N	k								
	2	3	4	5	6	7	8	9	10
4	F	III							
8		F	IV	III	III	III			
16			F	V	IV	IV	IV	III	II
32				F	VI	IV	IV	IV	IV
64					F	VII	V	IV	IV

$$N_{\text{fractional}} = m(n_l)^{k-q} \quad (2)$$

where q is the degree of fractionating. While an increase of q decreases the number of experiments, it may also cause loss of reliability in analyzing the results of experiments. A term commonly used to describe the reliability of an experimental design is *resolution*. The meaning of different resolutions is tied to the degree of aliasing in the fractional factorial design matrix. For example, in the case of resolution III, a design does not alias main effects with one another, but does alias main effects with two-way interactions. On the other hand, a design with resolution IV does not alias mains with two-way interactions, and is generally recommended to analyze two-way interactions effectively. Table 1 refers a guideline for available two-level factorial design with resolutions where F denotes full factorial design [9].

The results of DOE can be analyzed by evaluating the main effects for all factors and interactions for all of the two-way combinations. The main effect of the jth factor (E_j) and the interaction between the jth and kth factor (I_{jk}) are calculated as follows [10]:

$$E_j = \frac{\sum_{i=1}^{N} l_{ij} R_i}{\sum_{i=1}^{N} R_i} \quad (3)$$

$$I_{jk} = \frac{\sum_{i=1}^{N} (l_{ij} l_{ik}) R_i}{\sum_{i=1}^{N} R_i} \quad (4)$$

where N is the total number of experiments, R_i the response variable for the ith combination, l_{ij} equals -1 for the lower level, $+1$ to the upper level of the jth factor and is subjected to orthogonal condition as follows:

$$\sum_{i=1}^{N} l_{ij} = 0 \quad (j = 1, 2, \ldots, N) \quad (5)$$

In order to analyze the results of the experimental designs, analysis of variance (ANOVA) is utilized. The ANOVA is used to investigate the relationship between a response variable and one or more independent variables. It can be determined if the difference between the average of the levels is greater than what could reasonably be expected from the variation that occurs within the level. The test for ANOVA generally uses a ratio of:

$$F=\frac{\text{average}(SS_{\text{between}})}{\text{average}(SS_{\text{within}})}=\left[\frac{1}{n_g-1}\sum_{j=1}^{n_g}(n_j-1)\right]\frac{SS_{\text{between}}}{SS_{\text{within}}} \quad (6)$$

where SS_{between} and SS_{within} denote the square sum variation between groups, and the square sum variation within a group, respectively. Each term can be expressed as follows:

$$SS_{\text{between}}=n_j\sum_{j=1}^{n_g}(\bar{x}_j-\tilde{x})^2 \quad (7)$$

$$SS_{\text{within}}=\sum_{j=1}^{n_g}\sum_{i=1}^{n_j}(x_{ij}-\bar{x}_j)^2 \quad (8)$$

where n_g is the number of groups (levels), n_j the number of individuals in the jth group, x_{ij} the ith individual in the jth group, $\bar{x}$ the mean of the jth group, and $\tilde{x}$ the grand mean value.

3. DOEs for mold design

3.1. Selection of input variables

Coil separators are generally fabricated by injection molding with two cavities in a mold. Noryl PX9406 from GE Plastics was used as material. Fig. 1 shows the three-dimensional shape of the coil separator with its runner system. Three pin-point gates were employed with a main gate on the curved surface area and two sub-gates at the screen part. The design of the runner system (including gate design) is very important in terms of the flow characteristics. In the present work, four design parameters, positions of the sub-gate (A) and the main gate (B), and diameters of the sub-runner (C) and the main runner (D), were selected as input variables as shown in Fig. 2.

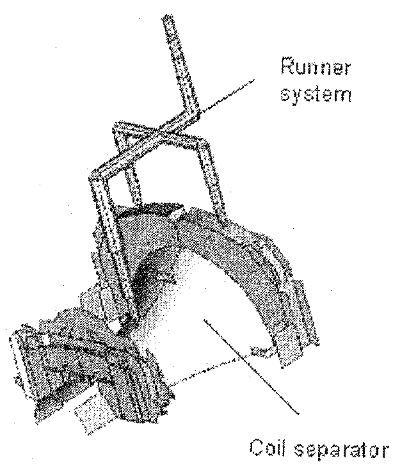

Fig. 1. Three-dimensional shape of a coil separator.

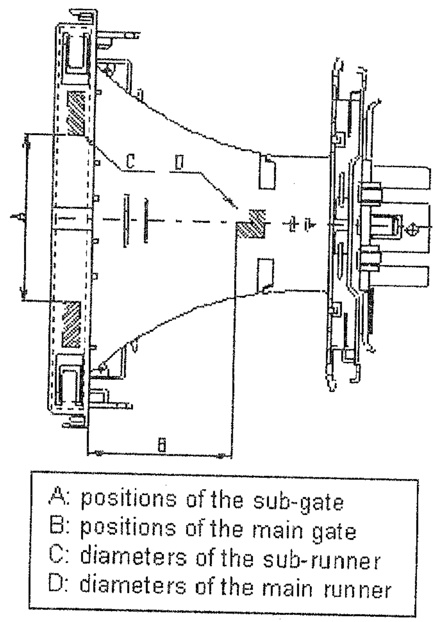

Fig. 2. Input variables for design of the runner system.

The cooling channels design is also important in terms of the overall productivity as well as the dimensional accuracy of the product. A well-designed cooling system improves cooling efficiency and thus reduces the cycle time of a product. However, a mold temperature that is too low may increase the melt viscosity, which degrades flow characteristics and increases the injection pressure. Therefore, cooling channels should be designed considering not only cooling efficiency but also related flow characteristics. In the present work, the layout of cooling circuits was also considered as a design parameter.

Fig. 3(a) represents the configuration of the current channel, while the temperature distribution at the end of cooling stage is shown in Fig. 3(b). The cooling time is set to 7.0 s, and the melt temperature and the coolant temperature are taken as 310 and 20 °C, respectively. It is observed that the temperature around the neck part is higher than other areas, as marked in Fig. 3(b), acting as a critical factor in delaying the cycle time. In order to increase cooling efficiency around the neck part, two modified cooling circuits were suggested as shown in Fig. 4.

3.2. Optimal design for injection mold

In order to perform DOE for mold design, numerical analyses were employed for various mold design parameters. C-MOLD was used for the analyses of the injection molding processes. The objectives for optimal injection molds design are defined as follows:

- *Minimum injection pressure*: estimated as injection pressure at the end of the filling stage.

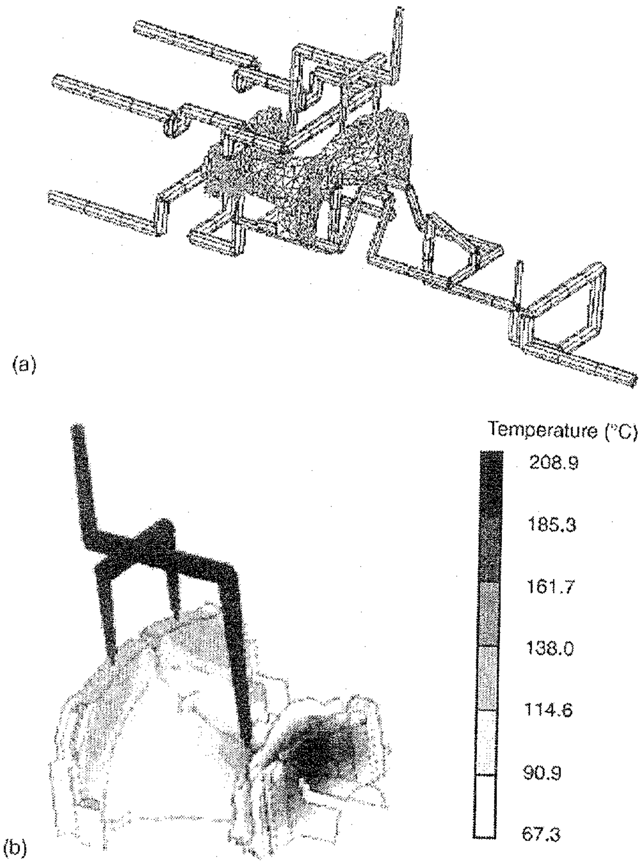

Fig. 3. Configuration of the original cooling system: (a) cooling channel 1 and (b) temperature distribution.

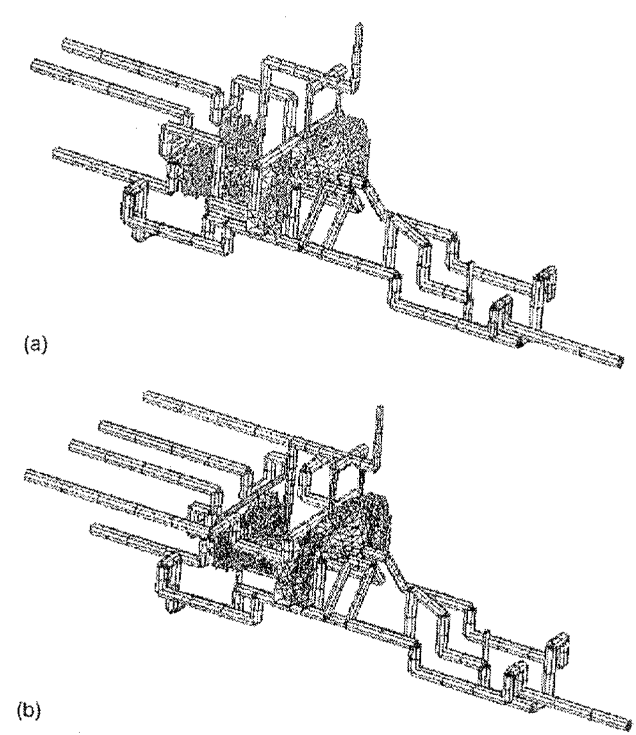

Fig. 4. Configurations of the modified cooling systems: (a) cooling channel 2 and (b) cooling channel 3.

- *Flow balance*: evaluated as the filling time difference between the screen part and the neck part.
- *Cooling efficiency*: estimated as the maximum temperature at the end of the cooling stage.

Since there are five factors, a large number of trials are required for full factorial experiments. In order to reduce the number of simulation trials, two-step screening DOE was introduced. For the first screening DOE, four factors related to the runner system were selected with two levels, as listed in Table 2.

Since the four factors above are related to the runner system, only the injection pressure and the filling time difference are compared. Fig. 5 shows the main effect plots for both objectives. Figs. 6 and 7 represent the interaction plots for the injection pressure and the filling time difference, respectively. Interaction plots are constructed by plotting both variables together on the same graph, and the distinguishing feature of strong interactions is the degree of non-parallelism between two lines. On this basis, it is clear that there is a strong interaction between only factors C and D in terms of the injection pressure (see Fig. 6).

Thus it can be concluded that the sub-runner diameter (B) has little effects and interactions for both objectives.

Table 2
Design for the first screening DOE

Factor	Description	Level 1	Level 2
A	Main runner diameter (mm)	4.5	6.5
B	Sub-runner diameter (mm)	3.5	5.5
C	Main gate position (mm)	30	40
D	Sub-gate position (mm)	30	50

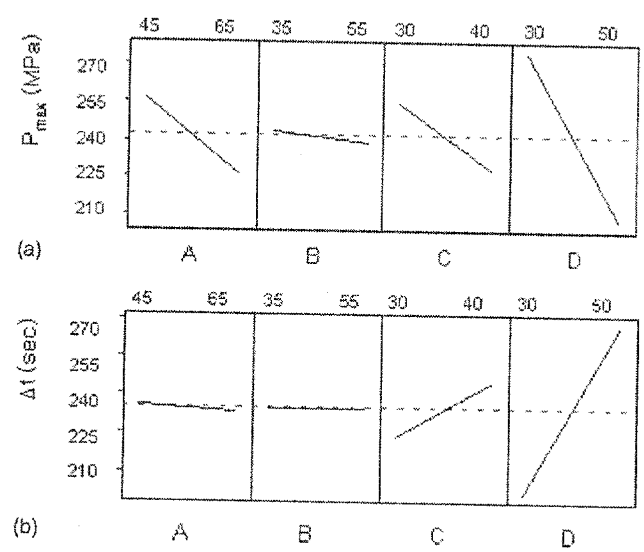

Fig. 5. Main effect plots for the first screening DOE: (a) main effect for P_{max} and (b) main effect for Δt.

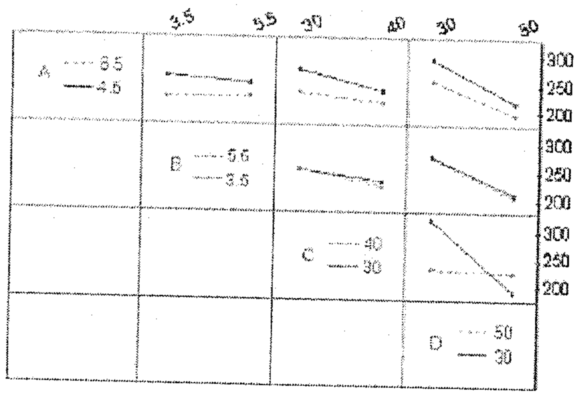

Fig. 6. Two-way interaction plot for P_{max}.

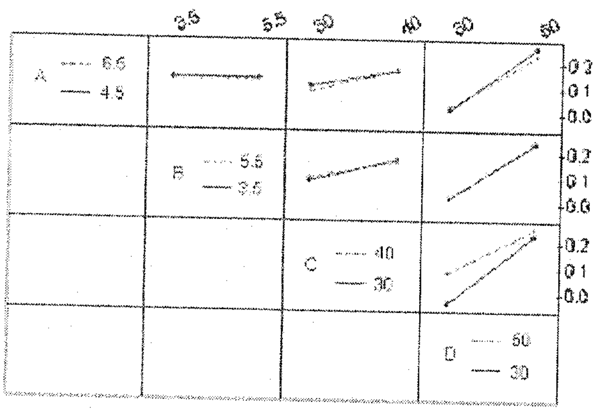

Fig. 7. Two-way interaction plot for Δt.

The sub-runner diameter was then removed from the design factors and was set to 4.5 mm, and a second screening DOE was carried out using the remaining factors. At the second DOE, the number of levels was set to 3 as listed in Table 3.

The results of the DOE were analyzed using the ANOVA approach. Desired candidates were selected among the full combinations with the following criteria: injection pressure must be less than 200 MPa and the time difference should be less than 0.1 s. Four candidates were then selected as shown in Table 4.

Table 3
Design for the second screening DOE

Factor	Description	Level 1	Level 2	Level 3
A	Main runner diameter (mm)	4.5	5.5	6.5
C	Main gate position (mm)	30	35	40
D	Sub-gate position (mm)	30	40	50

Table 4
Selected candidates and the corresponding results

No.	*A* (mm)	*C* (mm)	*D* (mm)	*P* (MPa)	Δt (s)
1	6.5	35	40	147.8	0.85
2	5.5	35	40	152.0	0.70
3	6.5	40	40	154.2	0.73
4	5.5	40	40	150.4	0.37

Table 5
Results of the final DOE for mold design

No.	*A* (mm)	*C* (mm)	*E* (mm)	*P* (MPa)	*T* (°C)
1	5.5	35	1	152.1	153.7
2	5.5	40	1	150.4	153.8
3	6.0	35	1	152.7	153.9
4	6.0	40	1	157.9	155.0
5	5.5	35	2	154.8	146.7
6	5.5	40	2	153.0	146.7
7	6.0	35	2	155.3	146.9
8	6.0	40	2	158.3	147.8
9	5.5	35	3	155.3	136.0
10	5.5	40	3	154.2	136.0
11	6.0	35	3	155.9	136.2
12	6.0	40	3	158.6	136.7

It is observed that all of the selected four candidates have the same values of the sub-gate position (*D*), 40 mm. This parameter was then removed and taken as 40 mm in the final experimental design. A final DOE for the mold design was carried out with an additional design factor, that is, the cooling channel configuration (*E*). Table 5 shows the design factors and the corresponding results for the final DOE.

From the above results, Case 10 was selected as the best candidate to improve flow characteristics and to reduce cycle time, and the optimal mold design parameters were determined as follows:

- main runner diameter: 5.5 mm,
- sub-runner diameter: 4.5 mm,
- main gate position: 40 mm,
- sub-gate position: 40 mm,
- cooling circuit type: type 3.

3.3. Comparison of cooling efficiency

In order to compare the cooling efficiency of the modified cooling circuit with that of the original one, temperature variations at several positions obtained from the numerical analysis are compared in Fig. 8. The maximum temperature was estimated around the neck part as previously shown in Fig. 3(b). In the original design, the maximum temperature was greater than the glass transition temperature (145 °C) even after 10 s. In the improved design, on the other hand, the maximum temperature falls below the transition temperature after only 4.5 s. Experimental verification for the improvement will be discussed further in the following section.

4. DOEs for process conditions

4.1. Selection of input variables

There are many process parameters that affect product quality of injection molding processes, including injection pressure, melt temperature, coolant temperature, injection

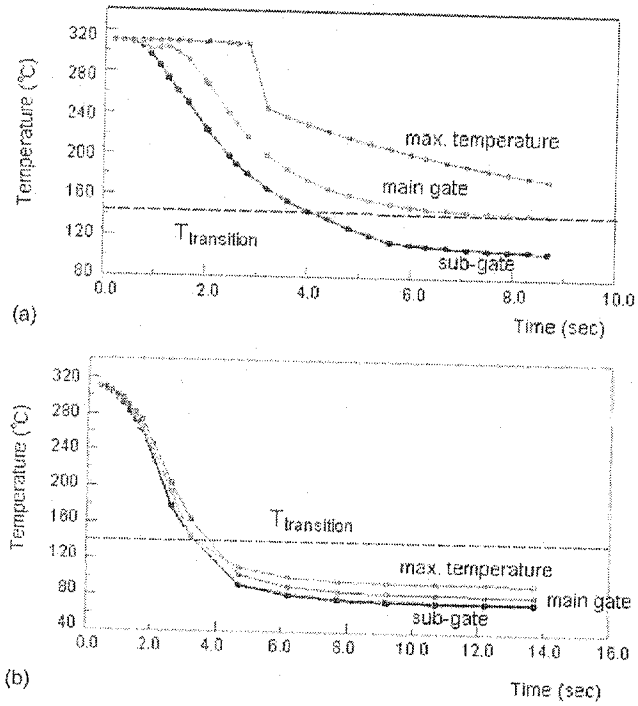

Fig. 8. Comparison of the temperature variations for: (a) the original design and (b) the improved design.

speed, packing pressure, packing time, cooling time, etc. Each parameter affects product quality in mutual interactions with other parameters as well as with separate factors.

Improper process conditions may have a detrimental effect on product quality. For example, insufficient injection pressure or lower injection rate may cause a short shot, while excessive injection pressure or packing pressure may cause flashes or part warpage. In the present work, process parameters related with injection conditions and packing conditions were selected as follows: injection pressure, injection speed, injection time, screw position, packing pressure, packing speed, and packing time.

4.2. Optimal design for process conditions

In order to perform DOE to determine the process conditions, experiments were carried out for the selected process parameters. An improved mold was fabricated for the experiments using the selected design parameters as discussed in the previous section. The objective for optimal process conditions is taken as the geometrical accuracy of the products, which is quantitatively measured as the weight of the products. Since there are eight factors, a screening DOE was also introduced in order to reduce the number of simulation trials. For the screening DOE, eight factors were selected with two levels and 32 runs as listed in Table 6. The experiments were carried out five times for each process condition.

Fig. 9 summarizes main effects and interactions for the mean part weight. The packing speed (*J*) and the screw position (*K*) appear to have relatively smaller effects and less interactions than other factors. The packing speed and the screw position were then set to 40% and 22 mm, respectively. A final DOE for mold design was then carried out using the remaining factors with 32 runs. The number of levels was set to 2 as shown in Table 7, and the results for the final DOE for process conditions are summarized in Table 8.

Table 6
Design for the screening DOE for process parameters

Factor	Description	Level 1	Level 2
F	Injection pressure (MPa)	105	110
G	Packing pressure (%)	30	50
H	Injection speed 1 (%)	50	58
I	Injection speed 2 (%)	50	70
J	Packing speed (%)	26	40
K	Screw position (mm)	22	26
L	Injection time (s)	1.3	1.5
M	Packing time (s)	0.5	2.0

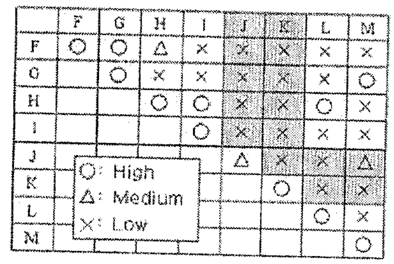

Fig. 9. Main effects and interactions for the part weight.

For the coil separator, the desired part weight is 28.3 g, and the measured values were between 27.26 and 28.63 g. It was observed that a short shot occurred where the part weight was less than 28.1 g. In the case where the part weight exceeded 28.6 g, on the other hand, a flash appeared around the parting surface. Desired candidates were selected among the 32 combinations within a range of 28.30 ± 0.02 g. The optimal process parameters to improve part quality were then determined using the ANOVA from these candidates as follows:

- injection pressure: 90 MPa,
- packing pressure: 50 %,
- injection speed 1: 62%,

Table 7
Design for the final DOE for process parameters

Factor	Description	Level 1	Level 2
F	Injection pressure (MPa)	85	90
G	Packing pressure (%)	40	50
H	Injection speed 1 (%)	58	62
I	Injection speed 2 (%)	30	58
L	Injection time (s)	1.5	1.6
M	Packing time (s)	1.0	1.5

Table 8
Results of the final DOE for process parameters

Exp. no.	*F*	*G*	*H*	*I*	*L*	*M*	Weight (g)	
							Mean	Variance ($\times 10^{-3}$)
1	85	40	58	58	1.6	1.5	28.07	1.048
2	90	50	62	30	1.5	1.0	28.41	1.030
3	85	50	58	30	1.5	1.0	27.75	44.677
4	85	50	62	58	1.6	1.5	28.42	6.978
5	85	50	62	30	1.5	1.5	28.30	3.771
6	90	50	58	30	1.5	1.5	28.32	0.403
7	90	50	62	30	1.6	1.5	28.63	0.483
8	90	40	58	58	1.6	1.0	28.28	1.057
9	85	50	62	58	1.5	1.0	28.14	1.859
10	85	40	58	30	1.6	1.0	28.00	0.540
11	90	50	62	58	1.6	1.0	28.53	0.684
12	85	50	62	30	1.6	1.0	28.35	4.651
13	90	40	62	30	1.5	1.5	28.36	1.121
14	90	40	58	58	1.5	1.5	26.16	3.800
15	85	50	58	30	1.6	1.5	28.31	7.073
16	85	50	58	58	1.6	1.0	28.15	1.255
17	90	50	62	58	1.5	1.5	28.49	2.850
18	90	40	58	30	1.6	1.5	28.36	6.457
19	90	40	62	30	1.6	1.0	28.49	1.247
20	85	40	58	58	1.5	1.0	27.26	22.073
21	90	40	62	58	1.6	1.5	28.53	2.343
22	90	40	58	30	1.5	1.0	27.98	1.283
23	90	50	58	58	1.5	1.0	28.18	0.915
24	90	50	58	58	1.6	1.5	28.47	4.099
25	85	40	58	30	1.5	1.5	27.26	8.404
26	90	50	58	30	1.6	1.0	28.38	2.695
27	85	40	62	30	1.5	1.0	27.98	0.947
28	90	40	62	58	1.5	1.0	28.28	3.554
29	85	40	62	30	1.6	1.5	28.29	0.382
30	85	40	62	58	1.5	1.5	28.12	1.828
31	85	50	58	58	1.5	1.5	27.92	14.960
32	85	40	62	58	1.6	1.0	28.20	0.577

- injection speed 2: 30%,
- packing speed: 40%,
- screw position: 22 mm,
- injection time: 1.5 s,
- packing time: 1.5 s.

4.3. Results and discussions

Reflecting the selected optimal process conditions, the quality and the productivity of the product have been improved in the following ways: the cooling time has been reduced by 50% (from 12 to 6 s) and the injection pressure has been decreased by 30%. The reduction of the injection pressure can decrease the occurrence of ejection troubles and improve the life cycle of molds. These kinds of quality improvement also guarantee the additional reduction of cycle time by reducing the number of defects and by saving the salvage time to repair molds. The total cycle time measured in the production fields then becomes 16 s, an improvement of 38% relative to the previous cycle time of 26 s.

5. Conclusion

In the present work, the optimal design for an injection molding process has been developed using the DOEs procedure and finite element analysis. All experiments were designed to be able to consider two-way interactions between various factors as well as main effects of individual factors. The proposed approach has been applied to the injection molding process of a deflection yoke, a precision electrical part with high geometric complexity.

The DOE approaches have been applied progressively for both mold design and process design. As the DOE for mold design, finite element analyses of the injection molding processes have been carried out. The optimal mold design specifications have been determined by analyzing the DOE results statistically. Then experiments were performed for various process conditions with additional DOE scheduling in order to determine optimal process parameters. As a result, the productivity of the product has been improved by 38% with better product quality. It is thus concluded that the proposed approach can be successfully reflected in the design procedures of industrial injection molding processes.

Acknowledgements

The support of the Seoul National University of Technology Grant is gratefully acknowledged.

References

[1] M.R. Kamal, S. Kenig, The injection mold of thermoplastic. Part I. Theoretical models, Polym. Eng. Sci. 12 (1972) 294–301.
[2] C.A. Heiber, S.F. Shen, A finite element/finite difference simulation of the injection molding filling process, J. Non-Newt. Fluid Mech. 7 (1980) 1–32.
[3] H.H. Chiang, C.A. Heiber, K.K. Wang, A unified simulation of the filling and postfilling stages in injection molding. Part I. Formulation, Polym. Eng. Sci. 31 (1991) 116–124.
[4] Y.S. Zu, S.T. Lin, Optimizing the mechanical properties of injection molded W-4.9% Ni-2.1% Fe in debinding, J. Mater. Process. Technol. 71 (1997) 337–342.
[5] R.S. Chen, H.H. Lee, C.Y. Yu, Application of Taguchi's method on the optimal process design of an injection molded PC/PBT automobile bumper, Compos. Struct. 39 (1997) 209–214.
[6] B.H. Min, Y.H. Kim, S.J. Lee, A study on plastic injection molding by Taguchi methods, in: Proceedings of the International Symposium on Advanced Forming and Die Manufacturing Technology, Pusan, 1999, pp. 733–739.
[7] AC Technology Inc., C-mold Reference Manual, Ithaca, New York, 1995.
[8] J. Krottmaier, Optimizing Engineering Designs, McGraw-Hill, New York, 1993.
[9] S.R. Schmidt, R.G. Launsby, Understanding Industrial Designed Experiments, Air Academy Press, Colorado, 1997.
[10] X. Lu, L.S. Khim, A statistical experimental study of the injection molding of optical lenses, J. Mater. Process. Technol. 113 (2001) 189–195.