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Optimal Design of Mold Layout and Packing Pressure for Automobile TCU Connector Cover Based on Injection Molding Analysis and Desirability Function Method

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사출성형 해석과 선호함수법에 기초한 자동차 TCU 커넥터 커버의 금형 레이아웃 및 보압의 최적 설계

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ABSTRACT

In this study, the optimal design of the multi-cavity mold layout and packing pressure for the automobile TCU connector cover is determined based on the injection molding analysis and the desirability function method for multi-characteristic optimization. The design characteristics to be optimized are the warpage and sink marks of the product, the scrap of the feed system, and the clamping force. The optimal design is determined by performing injection molding analysis and desirability analysis for design alternatives defined by a complete combination of five mold layouts and six-level packing pressure. The optimal design shows that the desirability values for individual characteristics are quite high and balanced, and the resulting values of individual characteristics are satisfactorily low.

Keywords : Injection Molding Analysis(사출성형해석), Desirability Function(선호함수), Multi-Characteristic Optimization(다특성 최적화), Mold layout(금형 레이아웃), Packing Pressure(보압)

1. Introduction

Injection molding is a process in which high-temperature polymer molten resin is injected into a cavity of a closed mold at high speed and then cooled for a period of time to make a product. When designing mold cavities for injection molding, it is often necessary to simultaneously consider the requirements for several design characteristics related to products, molds, and processes. However, due to the inherent features of injection molding, these design properties often conflict with each other, so the designer should come up with an optimal design as a compromise that reflects the designer's intentions for the design properties. In this regard, studies have

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been conducted on optimizing multiple design characteristics to simultaneously satisfy several design properties related to injection molding[1-6].

The automobile transition control unit (TCU) connector cover (TCC) is a component for protecting the terminals of the interface portion of the automobile TCU connector parts from foreign objects and external shocks. This study determines an optimal design of multi-cavity mold layout and packing pressure for molding of TCC based on injection molding simulation analysis and preference analysis. The design characteristics chosen to determine the multi-cavity mold layout (or mold layout) and packing pressure are the warpage and sink marks of the TCC, the scrap of the feed system, and the clamping force.

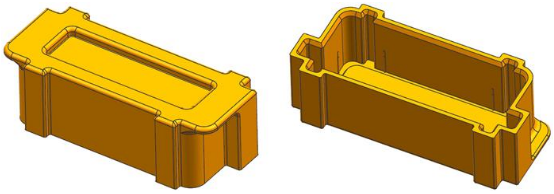
A desirability function method[7-9] was introduced to optimize the multiple selected design characteristics simultaneously. The desirability for a combination of values of the multiple design characteristics is evaluated by a total desirability function that incorporates designer-defined desirability functions for individual design characteristics.

In this study, injection molding simulations are performed for design alternatives defined by a complete combination of five mold layout designs and six-level packing pressure, and the optimal design is determined by the desirability analysis. The optimal design shows that the desirability values for individual design characteristics are balanced and fairly high and that the values of the individual design characteristics sufficiently meet the design tolerances.

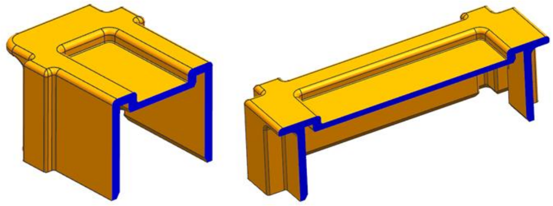
2. Design Alternatives of TCC Mold Layout and Design Characteristics

2.1 TCC model

Fig. 1 shows the shape and the cross-sections of a TCC product. The length, width, and height of



(a)



(b)

Fig. 1 Geometry of the TCC((a) 3D shape, (b) section shape)

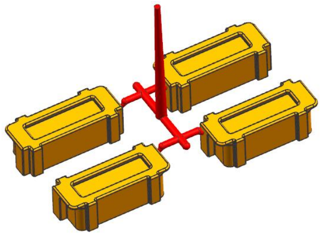
the TCC are 62.8mm, 26.8mm, and 20.2mm, respectively, and the wall thickness range is 1.5mm–1.8mm. The material of the TCC is polypropylene (PP), and the weight is 7.65g.

The TCC exhibits warpage and sink marks on the product after molding due to its geometric properties. Warpage deformation is observed on two parallel walls in the width direction on the open side of the product, which is caused by thermal imbalance and shrinkage deviations between the cavity and the core of the mold. In addition, the sink marks are observed on the two flat parts of the top surface of the product connected to the ribs on the back of the product.

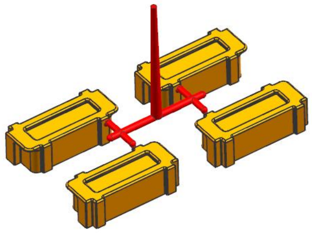
2.2 Design alternatives of TCC mold layout

To determine the optimal mold layout for the molding of TCC, the five mold layouts shown in Fig. 2 are considered as design alternatives. Table 1 shows the shape and dimensions of the main design elements for each mold layout.

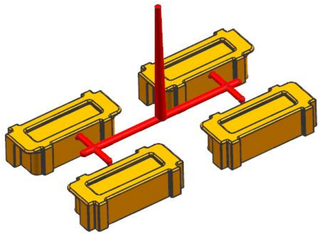
2.3 Design characteristics



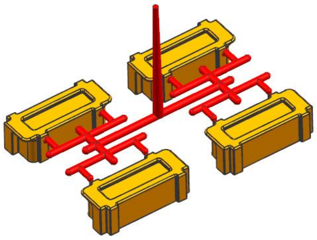
(a) Case #1



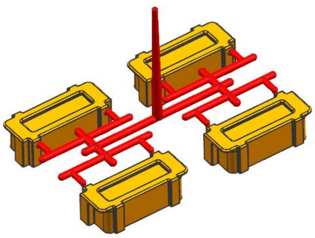
(b) Case #2



(c) Case #3



(d) Case #4



(e) Case #5

Fig. 2 Five design alternatives of TCC multi-cavity mold layout

Table 1 Design dimensions of TCC multi-cavity mold layouts

Case #				1	2	3	4	5
Number of gates				1			2	
Distance between gates (mm)				-			38.4	48.4
Feed system	gate	type		submarine				
		Φ (mm)	start	1.2				
			end	4			3.5	
		L(mm)		6				
	runner	type		non-tapered circular				
		Φ (mm)	1st	4.5			4.5	
			2nd	4			4.5	
			3rd	-			4.0	
			4th	-			3.5	
		L(mm)		31.05	35.45	56.55	83.55	88.75
	sprue	type		tapered circular				
		Φ (mm)	start	6.5				
			end	3.5				
		L(mm)		87				

The evaluation criteria chosen in this study to determine the optimal TCC mold layout are the product's formability and productivity.

The design characteristics for evaluating the formability of the TCC are warpage[10] and sink marks[11]. The warpage is measured as the maximum deflection between two parallel walls in the width direction from the open side of the product after molding. The sink mark is measured as the average value of the surface shrinkages at the nodes sampled on the two flat parts at the top of the product.

The design characteristics selected to evaluate the productivity of the TCC are the scrap of the feed system and the clamping force. The scrap is the weight of the gate, runner, and sprue determined after molding. The clamping force is the maximum force required to keep the mold closed during filling and packing.

3. Integrated Desirability of Multiple Design Characteristics

3.1 Overall desirability function

Let n design characteristics be $Y_i\,(i=1,2,\ldots,n)$. When the value of a design characteristic, Y_i, is the-smaller-the-better, the desirability function can be defined as follows[7].

$$f_i(Y_i)=\begin{cases}1 & Y_i \le Y_i^{min}\\ \left(\dfrac{Y_i - Y_i^{\max}}{Y_i^{\min} - Y_i^{\max}}\right)^r & Y_i^{\min} \le Y_i \le Y_i^{\max}\\ 0 & Y_i^{\max} \le Y_i\end{cases} \quad (1)$$

Here, $Y_i^{\min}$ and $Y_i^{\max}$ are, respectively, the minimum and maximum values of the design characteristics where the designer's desirability is not 0. The index r is a positive constant that defines the shape of the function and is subjectively determined by the designer.

If all desirability functions for individual design characteristics have been defined, the integrated desirability function to evaluate the overall desirability value can be defined by the following equation[8].

$$F=\left[f_1^{w_1}(Y_1)\times f_2^{w_2}(Y_2)\times \cdots \times f_n^{w_n}(Y_n)\right]^{1/\sum w_j} \quad (2)$$

Here, $w_i\,(i=1,2,\ldots,n)$ is the weight of the i-th design characteristic, and the sum must be 1.

The desirability for individual design characteristics has a value between 0 and 1, so the integrated desirability has a value between 0 and 1. The integrated desirability increases as the desirability values of individual design characteristics become more balanced. If the desirability for one design characteristic's value is 0, the integrated desirability is 0, regardless of the desirability values for other design characteristics. The combination of design characteristics like this one is completely unacceptable as a design solution.

3.2 Desirability functions of design characteristics and integration

Fig. 3 shows designer-defined desirability functions for design characteristics: warpage (Y_1), sink mark (Y_2), scrap (Y_3), and clamping force (Y_4). For all desirability functions, it is assumed that the designer's desirability value decreases linearly in a non-0 interval ($r=1$). The limits of the design characteristics allowed for each desirability function are 0.2mm for warpage, 0.02mm for sink mark, 10g for scrap, and 100ton for clamping force.

The desirability functions of individual design characteristics were integrated to form a total desirability function, as shown in eq. (3). As weights for each design characteristic, 0.4, 0.3, 0.2, and 0.1 were given to warpage, sink mark, scrap, and clamping force, respectively.

$$F=f_1^{0.4}(Y_1)\times f_2^{0.3}(Y_2)\times f_3^{0.2}(Y_3)\times f_4^{0.1}(Y_4) \quad (3)$$

Once the integrated desirability function has been defined for the overall design characteristics of the

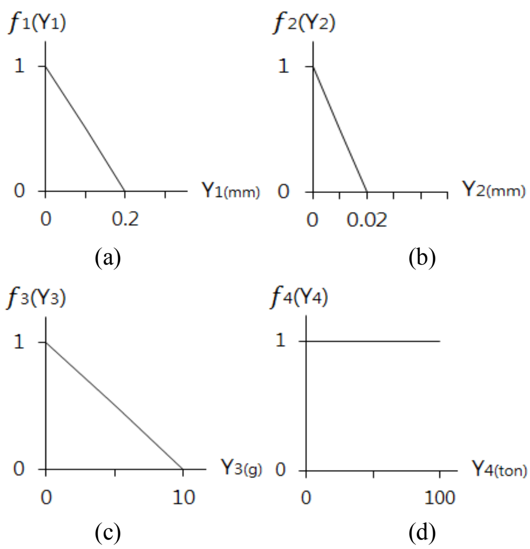


Fig. 3 Desirability functions((a) warpage, (b) sink mark, (c) scrap, (d) clamping force)

TCC mold layout, it is necessary to perform injection molding analysis and desirability analysis for the design alternatives of the TCC mold layout shown in Fig. 2 and determine the optimal design.

4. Injection Molding Analysis and Optimal Design Decision

4.1 Injection molding analysis

For each of the five mold layouts shown in Fig. 2, a finite element model was generated and injection molding analysis was performed. The four products consisted of a total of 144,512 triangular elements of the dual domain type,[12] and the feed system (i.e., gates, runners, and sprues) consisted of 132 to 340 1-dimensional elements of the beam type.

The resin used was PP, and the fill-pack-warp module of Moldflow Insight[12] was used as an injection molding simulator.

For the process conditions, the injection time, resin temperature, mold temperature, packing time, and cooling time were set to 2sec, 205℃, 30℃, 5sec, and 20sec, respectively. Meanwhile, the cooling analysis was not performed separately assuming uniform cooling of the mold. Among the process conditions, packing pressure was chosen as the process design variable, because it was judged to have the greatest effect on the warpage and sink marks of the TCC, scrap, and clamping force.

In this study, to determine an optimal design of the mold layout and packing pressure, we established 30 design alternatives given by a full factorial combination of the five mold layouts and six-level packing pressure and performed the injection molding analysis and desirability analysis for each design alternative. The six levels of packing pressure for the maximum injection pressure were 80%, 100%, 150%, 200%, 250%, and 300%.

4.2 Desirability analysis and optimal design decision

Table 2 shows the values of individual design characteristics measured from the injection molding analysis results for each design alternative. Table 3 shows the desirability values of the design characteristic values of Table 2 calculated using the corresponding desirability function. Table 4 presents the results of calculating the integrated desirability for each design alternative. Here, when the packing pressure was less than 100% of the maximum injection pressure, the integrated desirability values for all mold layout designs were all 0. This is because of the low packing pressures, which make the warpages exceed the allowable value ($0.2mm$), resulting in a 0 desirability for the warpages. However, even when the packing pressure was at a high level of 300%, the integrated desirability values in most of the mold layout designs were 0 or very low. This is because the warpage desirability became 0 or very low as the warpage increased due to excessive packing pressure. On the other hand, when the packing pressure level was 200% (50.42MPa), the integrated desirability was the highest in all mold layout designs, of which the integrated desirability value for Case #2 was the highest at 0.77. Therefore, we determined the mold layout of Case #2 and packing pressure of 200% as the optimal design.

In the optimum design, the desirability values for individual design characteristics were 0.70, 0.85, 0.72, and 1.0 for warpage, sink mark, scrap, and clamping force, respectively, so it was found that the level and balance of individual desirability values were quite high. Accordingly, the values of the design characteristics were expected to be 0.061mm, 0.003 mm, 2.79g, and 27.02ton for warpage, sink mark, scrap, and clamping force, respectively, and they showed satisfactory results. In addition, the optimal design has an advantage over other designs in terms of economics of mold production: The mold layout design has fewer runner branches than Case #4 and #5, so it is expected that the outer dimensions of the

Table 2 Values of individual design characteristics

Case #		1				2				3				4				5			
Characteristics (unit)		Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)
Packing pressure (%)	80	0.555	0.026	2.62	7.13	0.574	0.019	2.74	6.94	0.593	0.019	3.35	6.58	0.474	0.012	5.80	8.92	0.467	0.014	6.26	9.29
	100	0.407	0.022	2.63	10.53	0.433	0.015	2.75	10.29	0.475	0.016	3.36	10.04	0.357	0.009	5.82	13.37	0.349	0.011	6.28	13.92
	150	0.167	0.014	2.66	19.05	0.189	0.008	2.77	18.67	0.230	0.008	3.39	18.67	0.140	0.003	5.88	24.42	0.131	0.004	6.34	25.47
	200	0.062	0.006	2.67	27.52	0.061	0.003	2.79	27.02	0.101	0.001	3.41	27.28	0.066	0.000	5.92	35.42	0.063	0.000	6.39	36.94
	250	0.118	0.002	2.69	35.95	0.109	0.001	2.81	35.30	0.123	0.000	3.44	35.83	0.130	0.000	5.97	46.36	0.140	0.000	6.44	48.32
	300	0.205	0.000	2.71	44.36	0.190	0.000	2.83	43.60	0.183	0.000	3.46	44.36	0.222	0.000	6.01	57.30	0.235	0.000	6.49	59.79

Table 3 Desirability values of the design characteristic values

Case #		1				2				3				4				5			
Characteristics (unit)		Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)	Y_1 (mm)	Y_2 (mm)	Y_3 (g)	Y_4 (ton)
Packing pressure (%)	80	0	0	0.74	1	0	0.05	0.73	1	0	0.05	0.67	1	0	0.4	0.42	1	0	0.3	0.37	1
	100	0	0	0.74	1	0	0.25	0.73	1	0	0.2	0.66	1	0	0.55	0.42	1	0	0.45	0.37	1
	150	0.17	0.3	0.73	1	0.06	0.6	0.72	1	0	0.6	0.66	1	0.3	0.85	0.41	1	0.35	0.8	0.37	1
	200	0.69	0.7	0.73	1	0.7	0.85	0.72	1	0.5	0.95	0.66	1	0.67	1	0.41	1	0.69	1	0.36	1
	250	0.41	0.9	0.73	1	0.46	0.95	0.72	1	0.39	1	0.66	1	0.35	1	0.40	1	0.3	1	0.36	1
	300	0	1	0.73	1	0.05	1	0.72	1	0.09	1	0.65	1	0	1	0.40	1	0	1	0.35	1

Table 4 Integrated desirability values for design alternatives

Case #		1	2	3	4	5
Packing pressure (%)	80	0	0	0	0	0
	100	0	0	0	0	0
	150	0.32	0.26	0	0.49	0.5
	200	0.73	0.77	0.69	0.71	0.7
	250	0.64	0.68	0.63	0.55	0.5
	300	0	0.29	0.35	0	0

mold will be smaller and thus the cost of mold material and tooling will be lower. Fig. 4 shows the simulation results for the individual design characteristics of the optimal design.

5. Conclusions

This study's contents and conclusions are as follows.

1. Based on the injection molding analysis and desirability function method, the optimal design of the multi-cavity mold layout and packing pressure for the automobile TCC was determined.
2. The warpage and sink marks of the product, scrap of the feed system, and clamping force were selected as the design characteristics to be optimized, and the multiple design characteristics were optimized by using the overall desirability function that incorporates the individual desirability functions of the design characteristics.
3. The injection molding analysis and the

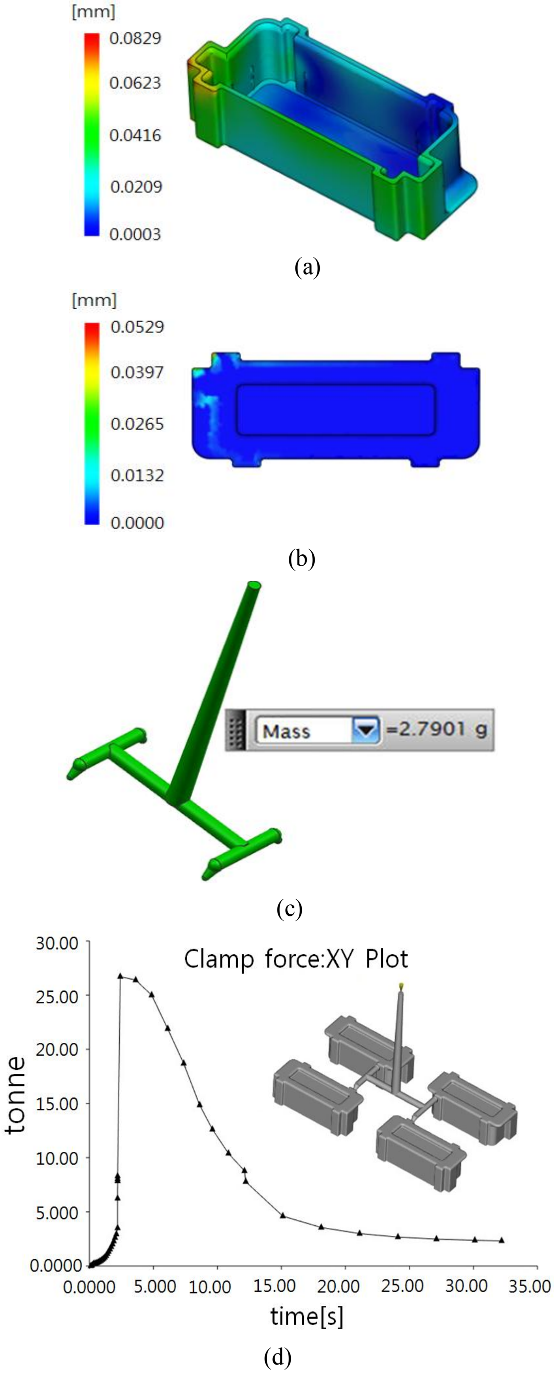


Fig. 4 Simulation results for optimal design((a) warpage, (b) sink mark, (c) scrap, (d) clamping force)

desirability analysis were performed for design alternatives defined by a complete combination of five mold layouts and six levels of packing pressure. As a result, the combination of the mold layout of Case #2 and the packing pressure of 200% was determined as the optimal design with the best integrated desirability of 0.77.

4. The optimal design produced satisfactory results in desirability and values for individual design characteristics: The desirability values of the warpage, sink mark, scrap, and clamping force were 0.70, 0.85, 0.72, and 1.0, respectively, which was fairly balanced with significant levels. The design characteristic values were expected to be 0.061mm, 0.003mm, 2.79g, and 27.02ton for warpage, sink mark, scrap, and clamping force, respectively.

Acknowledgment

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References

1. Yao, D., “Direct Search-Based Automatic Minimization of Warpage And Weldlines in Injection Molded Parts,” A Thesis for a Master, University of Massachusetts, pp. 1-135, 1998.
2. Liao, S. J., Chang, D. Y., Chen, H. J., Tsou, L. S., Ho, J. R., Yau, H. T. and Hsieh, W. H., “Optimal process conditions of shrinkage and warpage of thin-wall parts,” Polymer Engineering and Science, Vol. 44, No. 5, pp. 917-928, 2004.
3. Erzurumlu, T. and Ozcelik, B., “Minimization of warpage and sink index in injection-molded thermoplastic parts using Taguchi optimization method,” Materials and Design, Vol. 27, pp. 853-861, 2006.
4. Zhou, J. and Turng, L.S., “Adaptive Multiobjective Optimization of Process Conditions for Injection

Molding Using a Gaussian Process Approach," Advances in Polymer Technology, Vol. 26, No. 2, pp. 71-85, 2007.
5. Mehat, N. M. and Kamaruddin, S., "Multi-Response Optimization of Injection Moulding Processing Parameters Using the Taguchi Method," Polymer-Plastics Technology and Engineering, Vol. 50, No. 15, pp. 1519-1526, 2011.
6. Azaman, M. D., Wang, X., Zhao, G. and Wang, G., "Research on the Reduction of Sink Mark and Warpage of the Molded Part in Rapid Heat Cycle Molding Process," Materials and Design, Vol. 47, pp. 779-792, 2013.
7. Derringer, G. and Suich, R., "Simultaneous Optimization of Several Response Variables," Journal of Quality Technology, Vol. 12, No. 4, pp. 214-219, 1980.
8. Derringer, G., "A Balancing Act: Optimizing a Product's Properties," Quality Progress, Vol. 27, No. 6, pp. 51-58, 1994.
9. Del Castillo, E., Montgomery, D. C., and McCarville, D. R., "Modified Desirability Function for Multiple Response Optimization," Journal of Quality Technology, Vol. 28, No. 3, pp. 337-336, 1996.
10. Malloy, R. A., Plastic Part Design for Injection Molding, Hanser/Gardner Publishers Inc., Cincinnati, pp. 75-84, 1994.
11. Park, J. C., Yu, M. J., and Park, K. Y., "Design of Feed System and Process Conditions for Automobile Lamp Garnish Lens with Injection Molding Analysis," Journal of the Korean Society of Manufacturing Process Engineers, Vol. 18, No. 11, pp. 1-8, 2019.
12. Shin, N. H., Oh, H. S. and Kang, S. G., The Optimization of Injection Molding Process by CAE, Daekwangseorim, Seoul, pp. 327-422, 2010.