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DESIGN OPTIMIZATION OF AN INJECTION MOLD FOR MINIMIZING TEMPERATURE DEVIATION

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ABSTRACT−The quality of an injection molded part is largely affected by the mold cooling. Consequently, this makes it necessary to optimize the mold cooling circuit when designing the part but prior to designing the mold. Various approaches of optimizing the mold cooling circuit have been proposed previously. In this work, optimization of the mold cooling circuit was automated by a commercial process integration and design optimization tool called Process Integration, Automation and Optimization (PIAnO), which is often used for large automotive parts such as bumpers and instrument panels. The cooling channels and baffle tubes were located on the offset profile equidistant from the part surface. The locations of the cooling channels and the baffle tubes were automatically generated and input into the mold cooling computer-aided engineering program, Autodesk Moldflow Insight 2010. The objective function was the deviation of the mold surface temperature from a given design temperature. Design variables in the optimization were the depths, distances and diameters of the cooling channels and the baffle tubes. For a more practical analysis, the pressure drop and temperature drop were considered the limited values. Optimization was performed using the progressive quadratic response surface method. The optimization resulted in a more uniform temperature distribution when compared to the initial design, and utilizing the proposed optimization method, a satisfactory solution could be made at a lower cost.

KEY WORDS : Injection molding, Cooling channel, Cooling analysis, PQRSM, Design optimization

1. INTRODUCTION

The cooling stage is the longest stage during the cycle time of the injection molding process. Therefore, the most effective method to reduce the cycle time is to reduce the cooling time. The cooling time is fundamentally determined by the part thickness and mold temperature, which creates a cooling time limitation. If the mold temperature and part thickness are uniform over a whole part, the cooling time is not a concern; however, non-uniform part thickness and mold temperature distribution lengthen the overall cooling time. A longer cooling time means poor temperature uniformity, which can cause the part to warp. This is especially true for large products, such as automotive bumpers and instrument panels. It is for these types of parts that temperature uniformity becomes the most important factor in mold design.

We developed an automated optimization of the cooling circuit for an early part design in order to check the design validity. Usually the early part design is checked by the filing/packing and warpage analyses without a cooling analysis. This is because the assumption is that the mold temperature is uniform, which is not actually true. Providing a rapidly optimized cooling circuit for the designed part would help part designers correct their design (Koresawa and Suzuki, 1999).

The optimization was designed to minimize the part temperature deviation using design variables such as the diameters and distances of the cooling channels and baffle tubes and the depths of the part from the mold surface of the cooling channels and baffle tubes. A commercial computer-aided engineering (CAE) tool, Autodesk Moldflow Insight, was used for the cooling analysis. We successfully obtained an optimized cooling circuit in a time much shorter than can be achieved in a manual design. In order to develop the automated optimization of the cooling circuit for the practical mold design, practical design parameters such as the pressure drop limit and the coolant temperature rise were considered in the optimization.

The performance of the optimization technique can be affected by numerical noise in the responses. To find an optimum solution effectively when numerical noise exists, we performed an optimization by applying a regression-based sequential approximate optimizer known as the Progressive Quadratic Response Surface Method (PQRSM) (Hong *et al*., 2000), which was part of a commercial process integration and design optimization (PIDO) tool known as the Process Integration, Automation and Optimization (PIAnO) (FRAMAX, 2009).

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Figure 1. Finite element model of the product used for the optimization.

2. MODEL AND CHANNEL CONFIGURATION

2.1. Model Configuration

The model used for the optimization and CAE analysis was an automotive front bumper (FB). The size of the part was 1,800×600 mm, the element type was triangular and the number of elements in the model was approximately 26,000, with an average aspect ratio of 1.5. The model is shown in Figure 1.

2.2. Cooling Channel Configuration

The cooling circuit for the automotive bumper mold is typically designed to have a horizontal plane of line cooling channels and to install baffle tubes from the line cooling channels. However, in this design, unnecessarily long baffle tubes attached at a line cooling channel may cause a high pressure drop in the cooling channel. The line cooling channels may not contribute to mold cooling due to their large distance from the part surface. In order to improve the design, the line cooling channels were located along the offset profile of the part surface as shown in Figure 2. The end points of the baffle tubes were also located on the offset profile along a line cooling channel. Either the line cooling channels or baffle tubes were located on the offset profiles with equal arc distances between them.

3. FORMULATION

3.1. Design Constraints

The limitation of the pressure drop and the temperature rise between the inlet and outlet of cooling channel should also be considered in the design of the mold cooling circuit. A high pressure drop usually occurs in a needlessly long cooling circuit. In a long cooling circuit, the flow rate of coolant is low, which results in a high mold temperature and a high temperature rise at the outlet. The design defect could eventually be found in the cooling analysis; however, the optimization is already time consuming, so it is better to instead apply the limits as constraints in the optimization.

In this work we assumed that 4 line cooling channels were connected in series as a cluster, as shown in Figure 3. Clusters are connected in parallel by a manifold. Usually, the maximum pressure drop in a cluster is limited to 200 kPa, and the maximum temperature rise at the outlet is 5ºC (Menges *et al*., 2001). In the cooling analysis, each line cooling channel is regarded as a separate independent circuit for convenience. Because there were 4 line cooling channels in a circuit, the limits on the pressure drop and the temperature rise in each line cooling channel were 50 kPa and 1.25ºC, respectively. We also have an additional constraint due to the fact that the diameter of the baffle tube must be greater than or equal to the diameter of the cooling channel because the baffle tube has lower heat removal efficiency than the cooling channel. These three design constraints can be expressed as Equations (1), (2) and (3)

$$0\ Pa \le G_1 \le 50000\ pa\,, \tag{1}$$

$$0\ ^oC \le G_2 \le 1.2\ ^oC\,, \tag{2}$$

$$G_3 \le 0\ mm\,, \tag{3}$$

where G_1 is the constraint on pressure drop, G_2 is the constraint on temperature rise, and G_3 represents the subtraction of the diameter of the baffle tube from the diameter of the cooling channel.

3.2. Design Variables

In this work, the diameters, distances and depths of the line cooling channels and baffle tubes were chosen as design variables for optimization. The total number of design variables was 6 as shown in Table 1. Typically, the diameters of the cooling channels and baffle tubes are determined by the mold designer according to their rule of

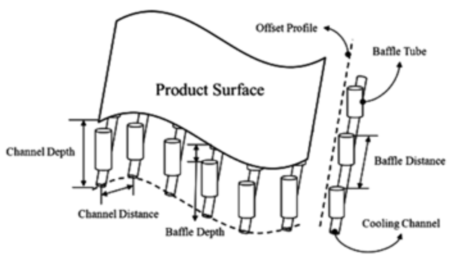

Figure 2. Configuration of cooling channels located along the offset profiles.

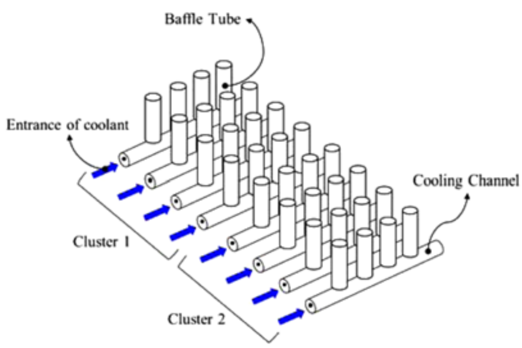

Figure 3. Clusters consisting of 4 cooling channels with baffle tubes.

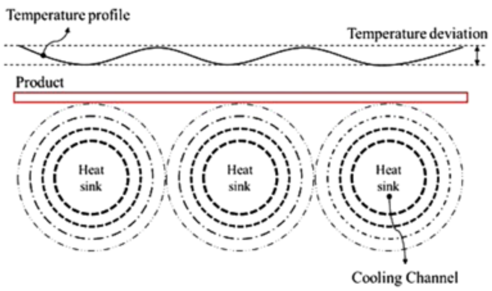

Figure 4. Scheme of the temperature field by the cooling channels.

Table 1. Lower and the upper bounds for design variables and the initial values for the optimization (unit: mm).

	Description	Lower	Initial	Upper
X_1	Channel diameter	10	30	40
X_2	Baffle diameter	10	30	40
X_3	Channel distance	60	90	120
X_4	Baffle distance	60	60	120
X_5	Channel depth	30	60	90
X_6	Baffle depth	30	60	90

thumb (Rhee *et al*., 2010). However, it has been examined in great detail among the mold designers. Table 1 shows the design variables with their ranges and initial values. The minimum values for the cooling channel distance, baffle distance and baffle depth were determined by the constraints of the machining requirement. The maximum values of cooling channel distance and baffle distance were determined by the empirical maximum obtained from the mold designers. The baffle distance was a discrete variable due to a restriction in the automated use of the CAE software. In this work, the baffle distances for optimization were 60, 90 and 120 mm.

3.3. Objective Function

A principal purpose of the mold cooling circuit optimization is to achieve uniform temperature distribution over the part. The uniform temperature distribution means that the temperature deviation caused by the cooling channels is minimized, as shown in Figure 4. The objective function in the optimization was the standard deviation of part temperature as shown in Equation (4). The part temperature was an arithmetic average of the upper and the lower surfaces of the mold halves. The mold surface temperature was calculated from the finite element of the part.

$$\min \qquad \sigma = \sqrt{\sum_{i=1}^{N} \frac{(E_i - E_w)^2}{N}}, \qquad (4)$$

where σ is the standard deviation of the part temperature, E_i is the temperature of i-th element, E_w is the average temperature of the entire triangular elements, and N is the number of elements.

4. OPTIMIZATION

4.1. Parametric Study

In order to examine the effects of the design variables on the objective function, pressure drop and temperature rise, parametric studies were carried out. A parametric study was performed by changing a variable in a certain range while keeping all other variables fixed. Figures 5-7 show the results of parametric studies for the objective function, pressure drop temperature rise, respectively. In each figure, the x-axis indicates the levels of design variables. Every design variable was divided into 11 levels from its lower bound to its upper bound. -5 and 5 mean the lower and upper bounds, respectively.

When examining the temperature deviation, the diameter of the cooling channels shows little influence to the objective function (see Figure 5.). This result was predictable because the cooling channel affects the part temperature to a lesser degree than the baffle tubes in the automotive bumper mold. The automotive bumper mold has a deep core so that the mold cooling depends upon the baffle tubes rather than the cooling channels. Another reason of the lack of influence can be that the flow state in the cooling channel remains turbulent in the range of the parametric study. The cooling channel usually has a smaller diameter than the baffle tube. When the flow in the baffle tube is kept in the turbulent state, the flow in the cooling channel will be in the turbulent state.

The diameters of the baffle tubes show a tangible influence when it increases above a certain value. Increasing of the diameter changes the flow in the tube to a laminar flow state. This is the cause for the lower heat transfer coefficient when compared to the turbulent flow state. This is why the temperature deviation becomes larger when the baffle tube diameter increases.

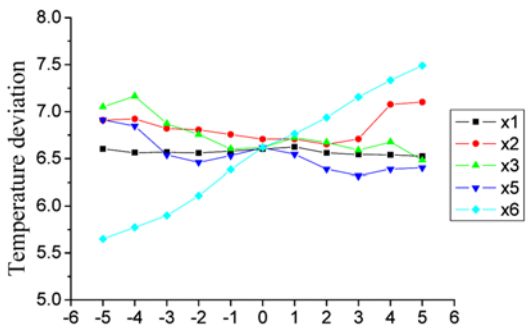

Figure 5. Parametric study result of temperature deviation (objective function).

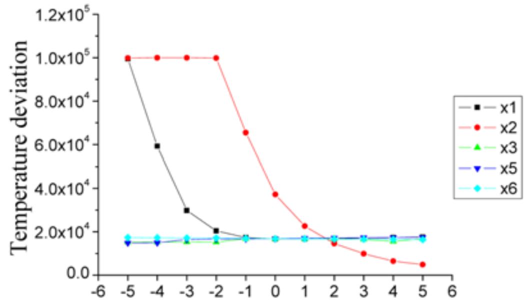

Figure 6. Parametric study result of the pressure drop.

Among all parameters, the baffle depth shows the largest influence on the objective function, as shown in Figure 5. As the baffle depth increases, the objective function increases. This means that the deeper location of the baffle tubes causes the temperature deviation to increase. Also, it confirms that the cooling of the automotive bumper mold depends upon the baffle tubes.

The diameters of the cooling channels and the baffle tubes have the highest influence on the pressure drop in the cooling circuit, while the other variables show little influence (see Figure 6.). As the diameters increase, the pressure drop decreases after a certain value. This is also a predictable result as a larger diameter decreases the pressure drop.

The influences of the temperature rise at the outlet are shown in Figure 7. The most influential parameters are the baffle diameter and the channel distance. The influence of the baffle diameter shows the highest values in the range from -1 to 3. In the case of the smaller baffle diameter, the reduced surface area for the heat transfer may cause a smaller temperature rise, while the larger baffle diameter may cause the lower heat transfer coefficient due to the lower flow rate.

The increased channel distance means that each cooling channel takes up a larger area of the part surface with a larger amount of heat removal. This may give a physical explanation to why the increase of the temperature rise increases with channel distance. The fluctuations shown in Figure 7 are supposed to be numerical noise.

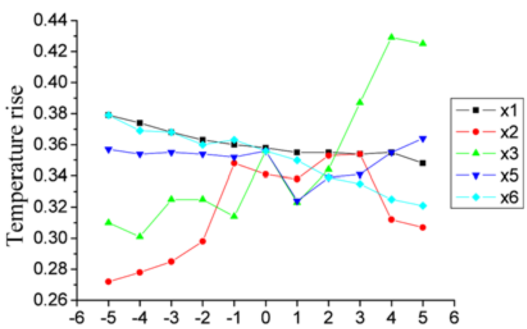

Figure 7. Parametric study result of the temperature rise.

4.2. Optimization Results

The largest increase in the temperature rise (Figure 7) is approximately 0.15ºC. This value is much less than the constraint. The influence of the variables on the temperature rise is not tangible.

The baffle distance was considered the discrete variable in this work; hence, it was difficult to apply a general optimization method. Because there were three values, optimizations were carried out 3 times with the 5 design parameters. The baffle distance was fixed in each optimization.

Figures 8 and 9 show the temperature deviations as the channel diameter, x_1 and the channel distance, x_3 change by 0.1% using the perturbation method around their initial design values. From these results we recognized that the variations in the temperature deviations as x_1 and x_3 varied included numerical noise.

Therefore, we chose PQRSM as the optimization method that could effectively optimize the response with numerical noise. The PQRSM equipped in a commercial

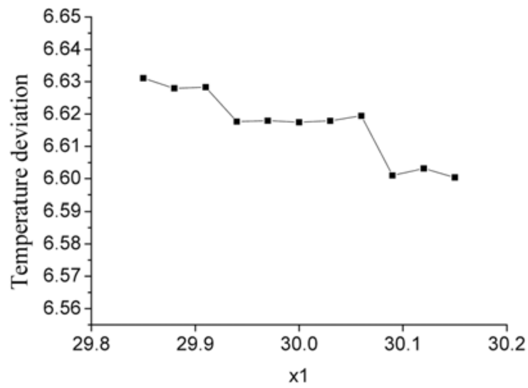

Figure 8. Variation of the temperature deviation w.r.t. x_1 observed by using 0.1% perturbation method.

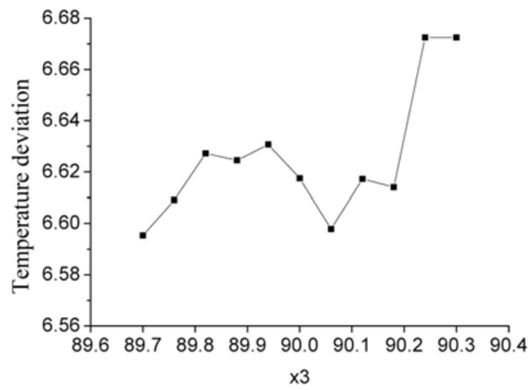

Figure 9. Variation of the temperature deviation w.r.t. x_3 observed by using 0.1% perturbation method.

Table 2. Optimization results summary.

	Lower	Baseline	X_4=60	X_4=90	X_4=120	Upper
x_1	10.00	30.00	29.67	28.39	30.00	40.00
x_2	10.00	30.00	30.36	28.39	30.00	40.00
x_3	60.00	90.00	89.37	90.29	88.13	120.00
x_4	60.00	60.00	60.00	90.00	120.00	120.00
x_5	30.00	60.00	87.63	88.81	90.00	90.00
x_6	30.00	60.00	30.00	30.00	30.00	90.00
OBJ		6.62	5.35	5.60	5.46	
G_1	0	16790	16904	16610	8758	50000
G_2	0	0.36	0.43	0.33	0.38	1.20
G_3		0.00	-0.69	0.00	0.00	0.00

PIDO tool, PIAnO, approximates the objective function and constraints with quadratic functions in the trust region, and it sequentially moves and reduces the trust region until it finds the optimum solution.

The results of the optimization using the PQRSM are shown in Table 2. Baseline represents the standard condition before applying the optimization. After the optimizations were carried out for the 3 cases of the baffle distance (x_4), the lowest temperature deviation was obtained in the case of a baffle distance of 60 mm. Therefore we conclude that a baffle distance of 60 mm is our optimized result.

At this optimized result, the temperature deviation was reduced by 19.2% compared to that of the baseline design while satisfying all other design requirements. Among the design variables, the channel diameter, x_1, the baffle diameter, x_2 and the channel distance, x_3 remained close to their initial values while the channel depth, x_5 moved toward the upper bound and the baffle depth, x_6 toward the lower bound. Thus, we expect a better result if the bounds of the baffle distance, x_4, channel depth, x_5 and baffle depth, x_6 can be relaxed.

5. CONCLUSION

In this study, we carried out the optimization of the cooling circuit for an automotive front bumper. The design objective was to minimize the temperature deviation while satisfying all constraints. There were three design constraints that included the pressure drop, temperature rise and aspect ratio, in addition to side constraints on six design variables.

Among the six design variables, the baffle distance was the discrete design variable. Thus, we carried out optimizations for the three cases of baffle distances being 60, 90 and 120 mm. The lowest temperature deviation was obtained in the case of a baffle distance of 60 mm. In this case, the temperature deviation was reduced by 19.2% compared to the baseline design while satisfying all design requirements. It is believed that the design optimization approach of employing CAE and PIDO tools adopted in this study can be applied for the design of many industrial manufacturing processes.

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