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REGULAR PAPER

Design of Advanced Injection Mold to Increase Cooling Efficiency

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Abstract

Cycle time reduction is one way to increase the energy efficiency of the injection molding production process. For injection molding, conformal cooling channels can be considered as a potential solution for obtaining a uniform temperature distribution in the mold, which results in a shorter cooling time and better quality of the molded part. However, the design and manufacture of optimal cooling channels is a challenge due to their complex geometry and heat transfer. This paper presents a method to maximize the efficiency of a conformal cooling channel made by 3D printing technology. The combination of analytical formulas and CAE simulation is applied to design optimal cooling channels in terms of cooling efficiency and manufacturability. An actual case study is introduced and analyzed to demonstrate the benefit of the conformal cooling channel and the robustness of the proposed design method. The results show that the cooling time and cycle time can be reduced more than 50% when molding a plastic product that is difficult to cool by conventional straight-drilled cooling channels. This is a great contribution to an environmentally friendly manufacturing technology.

Keywords Design optimization · Injection mold · Conformal cooling channel · Manufacturing efficiency · Energy saving

1 Introduction

Injection molding is the most popular method for making plastic products by mass production. Therefore, if the cycle time is reduced, great benefits from the reduction of energy consumption and manufacturing cost are obtained. The molding process comprises four stages, including filling, packing, cooling, and ejecting the molded part. Of these, the cooling step takes the longest time and accounts for two-thirds of the molding cycle. In addition, the cooling process also affects the quality of the molded part because uniform cooling results in a minimum of warpage and the least shrinkage and thermal residual stress. Hence, the cooling channel plays a critical role in the injection mold. Traditionally, cooling channels are straight-drilled for ease of manufacturing. However, straight cooling channels cannot produce uniform and effective cooling performance if the shape of the molded part is in free form. Recently, with the advancement of rapid prototyping, conformal cooling channels made by 3D printing technology have become commonly used in the injection molding industry [1–5]. Three-dimensional printing has emerged as a green manufacturing technology with great benefits, such as less material consumption and more efficient production [6].

The specific energy consumption, cost, and environmental impact of the injection molding process depends not only on the injected thermoplastics and the type of injection molding machine [7], but also on the process parameters and the mold itself. An injection mold with an advanced design of the cooling system will produce better quality products and a shorter cycle time. Many publications have reported that conformal cooling channels are better than straight-drilled cooling channels for complex mold surfaces, which are impossible or difficult to cool with conventional methods. This new kind of cooling channel has drawn considerable injection mold designer attention. The main benefits of conformal cooling channels are the reduction of cycle time and less warpage of molded parts [2, 8–10]. For example, Ahn et al. [11] manufactured an injection mold by laser-aided direct metal rapid tooling method for molding an electric fan, and demonstrated that the cooling time was reduced by

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approximately 35%. Such a reduction of cooling time leads to increased productivity and reduced manufacturing cost.

Because of the geometrical freedom of metal rapid tooling methods such as selective laser sintering (SLS) and selective laser melting (SLM), conformal cooling channels can be manufactured with flexible cross sections and topologies. The spiral conformal cooling channel is the most common deployment [5, 12, 13] because this kind of cooling channel results in a nearly constant coolant velocity, although the pressure drop may be high. In contrast, scaffold-type conformal cooling channels [14, 15] and Voronoi diagram-type channels [12, 16] have low pressure drops, but it is difficult to achieve uniform coolant velocity, and stagnation in some channel segments can occur.

The influence of channel cross section on cooling performance has been analyzed by Jahan et al. [17–19]. Rectangular channels have proved to be most effective in terms of cooling performance, but this type of cross section might not satisfy the manufacturability requirements of the additive manufacturing method. Elliptical, round, and water-drop-shaped cross sections are easier to print without support structures and are free of stress concentrations.

Although conformal cooling channels are now considered to be better than conventional cooling channels, their best performance is obtained only when they are well designed and optimized. A few researchers have studied the optimization of conformal cooling channels, but there has not been intense focus on how to design the best conformal cooling channel. Jahan and El-Mounayri [9] and Wu et al. [20] studied methods to optimize cooling channel parameters for a simple cylindrical shape using simulation and design of experiment. Various other researchers [2, 11, 21] developed optimal designs for cooling channels that can increase the effectiveness of the cooling system in the mold, but these designs have been restricted by relatively simple cooling channel configurations.

A complex molded part requires a more complicated cooling channel design than does a simple mold. Therefore, our work focuses on a method that maximizes the efficiency of a complex conformal cooling channels made by 3D printing technology, in which the manufacturability is also considered. The next sections of this paper present the details of the theory, method, and case study results. Some conclusions and discussions of future work are given in the last section.

2 Theoretical Background and Method

2.1 Relationship Between the Cooling System and Cooling Time

The cooling time depends on the thickness of the molded part, the material properties, and the process parameters:

$$t_c = \frac{s^2}{\pi^2 a} \ln\left[\frac{4}{\pi}\left(\frac{T_M - T_W}{T_E - T_W}\right)\right] \tag{1}$$

where s is the part's thickness; T_M, T_W, and T_E are melt temperature, average mold surface temperature, and ejection temperature, respectively; and a is the thermal diffusivity of the polymer.

$$a = \frac{k_p}{\rho c_p} \tag{2}$$

where, ρ, k_p, c_p are the density of the polymer, its thermal conductivity, and its specific heat, respectively.

The melt temperature or injection temperature depends on the thermal properties of the plastic material, and it can be considered a fixed selected parameter. The mold temperature and ejection temperature are also recommended by the plastic supplier. Thus, T_M and T_E are fixed as predetermined process parameters. In contrast, the average mold surface temperature T_W depends on the geometry, the deployment of the cooling channels, and the coolant temperature.

To derive the relationship between cooling time and the parameters of the cooling system, we consider the thermal equilibrium equation in the mold. The heat flux from the polymer and the heat flux taken by the coolant must be balanced (neglecting the heat exchange with the surrounding environment):

$$\dot{Q}_m + \dot{Q}_c = 0 \tag{3}$$

where the heat flux from the hot plastic into the coolant can be calculated as [22]

$$\dot{Q}_m = 10^{-3}[c_p(T_M - T_E) + i_m]\rho \frac{s}{2} x \tag{4}$$

where i_m and x are the latent heat of the polymer and the pitch between the cooling channels, respectively (see Fig. 1).

The heat flux transferred to the coolant in time t_c amounts to [23]

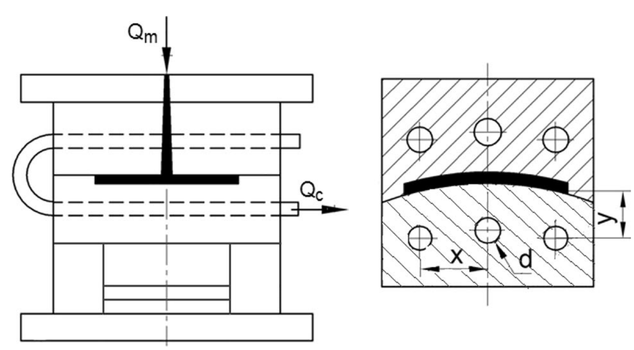

Fig. 1 Physical modeling of heat flow (left) and sketch of the cooling system in an injection mold (right)

$$\dot{Q}_c = 10^{-3} t_c \left(\frac{1}{10^{-3}\alpha\pi d} + \frac{1}{k_{st}S_e} \right)^{-1} \left(T_W - T_C \right) \tag{5}$$

where k_{st}, d, S_e, and T_c are the thermal conductivity of the mold steel, the diameter of the cooling line, the shape factor, and the coolant temperature, respectively.

The influence of the cooling channel position on the heat conduction is considered by applying shape factor [24]:

$$S_e = \frac{2\pi}{\ln\left[\frac{2x\sinh(2\pi y/x)}{\pi d}\right]} \tag{6}$$

where y is the distance from the center of the cooling line to the mold surface (see Fig. 1).

The heat transfer coefficient of the coolant is calculated by [25]

$$\alpha = \frac{31.395}{d} R_e^{0.8} \tag{7}$$

where the Reynolds number is:

$$R_e = u\frac{d}{\nu} \tag{8}$$

where d, u, and ν are the diameter of the cooling line, the velocity of the water, and the kinetic viscosity of the water, respectively.

By combining Eqs. (1) through (8), we can derive the following equation:

$$\frac{[c_p(T_M - T_E) + i_m]\rho\frac{s}{2}x}{T_W - T_C}\left\{\frac{1}{2\pi k_{st}}\ln\left[\frac{2x\sinh\left(2\pi\frac{y}{x}\right)}{\pi d}\right] + \frac{1}{0.03139\pi R_e^{0.8}}\right\} = \frac{s^2}{\pi^2 a}\ln\left[\frac{4}{\pi}\left(\frac{T_M - T_W}{T_E - T_W}\right)\right] \tag{9}$$

There are three geometric variables in Eq. (9), x, y, and d, and an equation with three variables yields an infinite number of solutions. To solve this equation, the constraints showing the relation of $x=\beta_1 d$ and $y=\beta_2 d$, in which $2\le\beta_1\le 5$ and $1\le\beta_2\le 5$, should be used to reduce the number of variables. Equation (9) is an analytical method that can be used to support the design of the cooling channels in an injection mold.

2.2 The Possibility of Minimizing Cooling Time

When designing conformal cooling channels made by 3D printing technology to replace conventional ones, the goal is to determine what percent of cooling time reduction can be obtained. This is important data for the decision of investing in conformal cooling channels made by 3D solid free-form fabrication. Using Eq. (1), the relationship between cooling time and the mold surface temperature can be derived when the molded part's thickness, the thermal properties of the polymer, the melt temperature, and the ejection temperature are identified and kept constant. The chart in Fig. 2 shows that the cooling time increases exponentially with the mold temperature. Therefore, if the actual mold temperature is high, the potential of cooling time reduction is great. In contrast, if the actual mold temperature is low, the percentage of cooling time reduction is small.

For example, assuming the average surface temperature of a mold region is about 84 °C when applying a conventional straight-drilled cooling channel. The ejection temperature is 87 °C, the molding thickness is 2.5 mm, and $T_M = 240$ °C. The plastic material is polypropylene with an average specific heat and thermal conductivity of 1454 J/kg °C and 0.168 W/m °C, respectively. In this case, the ideal cooling time is around 23 s. If the mold surface temperature decreases to 44 °C, the cooling time reduces to around 10 s, a reduction of approximately 56.5%. The cooling time can only be reduced to a minimum when the mold surface cools down to the lower range of the recommended mold temperature. However, if the mold surface temperature is too low, the cooling speed increases, but short shots and high residual stress in the molded parts can occur.

2.3 The Method of Optimizing a Conformal Cooling System in an Injection Mold

The objective of optimizing the cooling system is to minimize both the cooling time and mold wall temperature deviation. If the mold wall temperature is not distributed evenly, the molded part will be significantly warped and the cooling time will increase, and vice versa. However, for a specified molded part with a certain thickness and predefined process parameters, the cooling time depends only on the mold temperature. Therefore, minimizing the cooling time is

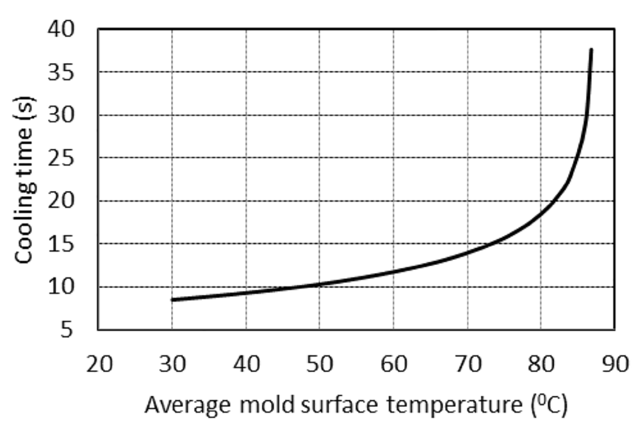

Fig. 2 An example of the relationship between cooling time and mold temperature

equivalent to holding the mold temperature low as possible as a constraint, and the mold temperature deviation should also be minimized.

To design an optimized cooling channel, the analytical formulas in Sect. 2.1 can be used to estimate the cooling channel geometry. However, conformal cooling channels are complex in terms of geometry and heat transfer, and therefore a finite element-based simulation method can be adopted, as shown in the algorithm in Fig. 3. Strategic changes in the geometry of the cooling channel based on these optimization techniques will result in an optimal design where the target mold temperature and the least temperature deviation (i.e., an even temperature distribution) are obtained.

The fundamental principle of heat transfer in the algorithm in Fig. 3 is summarized as follows.

The heat transfer in the molded part can be approximately considered as a 1D heat transfer problem in a plate. The temperature distribution in the molding is modeled by the following equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \tag{10}$$

The partial differential Eq. (10) can be solved conveniently by the finite difference method. Because of the thermal contact resistance between the polymer and the mold, a convective boundary condition is applied instead of an isothermal boundary condition:

$$h_c\left[T_{ps} - T_M\right] = -k_p \frac{\partial T}{\partial z} \tag{11}$$

where h_c and T_{ps} are the heat transfer coefficient in the mold-polymer interface, and the molded part surface temperature, respectively.

The heat flux across the mold-polymer interface is written as:

$$q = -k_p \frac{\partial T}{\partial n} \tag{12}$$

where n is the normal vector of the surface.

The cycle-averaged heat flux is calculated by:

$$\bar{q} = \frac{1}{t_c} \int_0^{t_c} q dt \tag{13}$$

where t_c is the cooling time calculated by Eq. (1) in Sect. 2.1.

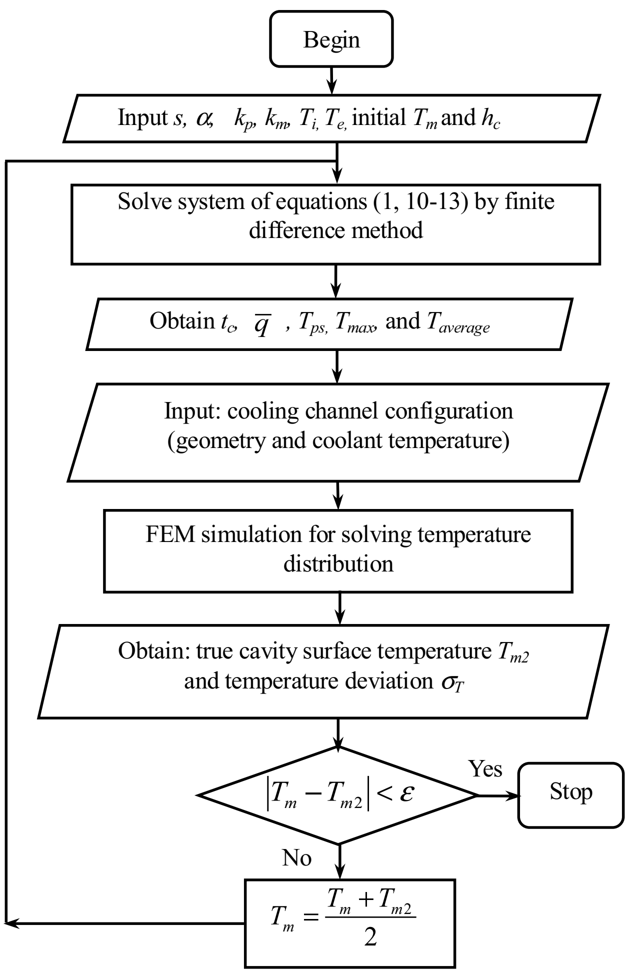

Fig. 3 Algorithm for calculating mold temperature, temperature distribution, and cooling time [26]

3 Case Study

To demonstrate the maximum efficiency of the conformal cooling channel made by 3D printing technology, we conducted a case study. A molded part made of polypropylene material with 2.5 mm thickness, maximum diameter of 87 mm, and volume of 58 cm^3 was selected, as shown in Fig. 4. The recommended melt temperature, mold temperature, and ejection temperature were 240 °C, 45 °C, and

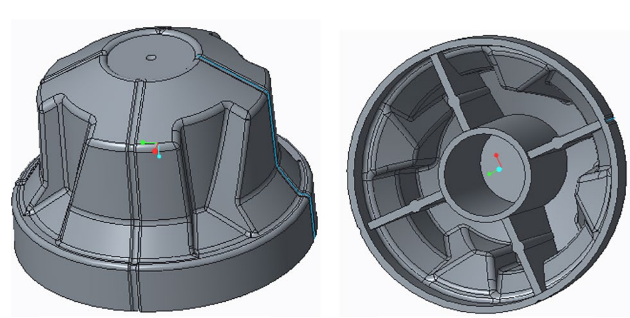

Fig. 4 The molded part for the case study

85 °C, respectively. The inlet water temperature was 20 °C. Because of the deep and narrow slots in the product, it was difficult to cool the molded part in the core mold side by using conventional cooling channels. Although a conventional cooling system with baffles and high thermal conductivity material (41 W/m°K) were applied, the mold core temperature was very high (80.7 °C when the cooling time was 22 s; see Fig. 5). If the cooling time was increased to 40 s, the maximum mold surface temperature at the end of the cooling process was approximately 60.8 °C (Fig. 5c). In addition, the temperature distribution was uneven (the deviation of temperatures was around 30 °C). The cooling time to reach the ejection temperature for the whole molded part was approximately 22 s; however, it took only 9.7 s to cool the flat part with the same thickness. Therefore, there was great potential for reducing the cooling time by applying a conformal cooling channel.

Based on the geometry of the molded part, the deployment of the cooling channel was determined as shown in Fig. 6, in which the hot surfaces needed cooling channels near them. In addition, the channels had to be smooth and had to satisfy the manufacturability of 3D printing in which the minimum wall thickness, the minimum hole diameter, and the support-free structure had to be strictly considered.

The next step in optimizing the design of the conformal cooling channels was to configure the cross sections of the channels in such a way that the mold temperature deviation was minimized and the target mold temperature was achieved and was low enough. If these conditions could be met, the cooling time would be minimized. Because the simulation of a 3D cooling system is time-consuming, the problem can be simplified as a 2D heat transfer to reduce the computing cost. In this case study, based on the geometry of the cooling channels, two important cross sections were considered, as shown in Fig. 6 (cross Sect. 1 and vertical Sect. 2). A Python script that automatically runs in the Abaqus CAE tool was used to simulate the temperature

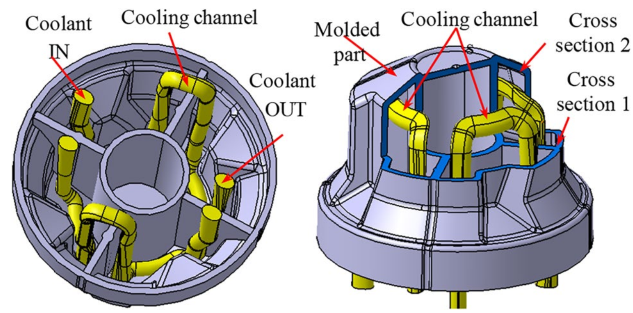

Fig. 6 The conceptual geometry of the conformal cooling channel

distribution and to optimize the cross sections of the cooling channels. For the section in the Fig. 7, the parallelogram gave the lowest temperature deviation compared to the ellipse and the circle shape. However, a parallelogram can result in a crack when printing the mold core. In terms of heat transfer, the ellipse shape was better than the circle shape in this case study because the perimeters of the ellipses were greater than those of the circles with the same area of cross section.

In the top region of the mold core, the cross section of the cooling channel should be in the form of an ellipse or a water drop shape for the manufacturability of 3D printing (Fig. 8). The drop-shaped cross section resulted in the lowest temperature deviation of the mold surface, meaning that the temperature was distributed more evenly with the water drop shape cross section.

The performance of a cooling channel increases when the mold material has high thermal conductivity. Unfortunately, steel with high thermal conductivity usually has a high carbon content, and hot cracks often occur. Therefore, the preferred material for printing mold cores by the SLS method is maraging steel. The thermal conductivity of this material is quite low (23 W/m°K), and its low carbon and high strength reduce the likelihood of printing cracks.

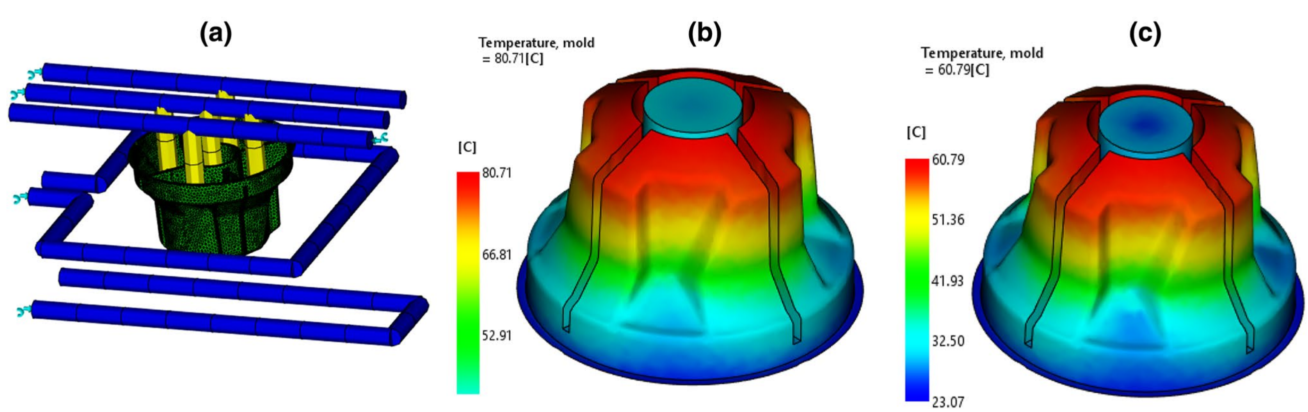

Fig. 5 Conventional cooling channel (**a**), temperature distribution in mold core with 22 s (**b**) and 40 s of cooling time (**c**)

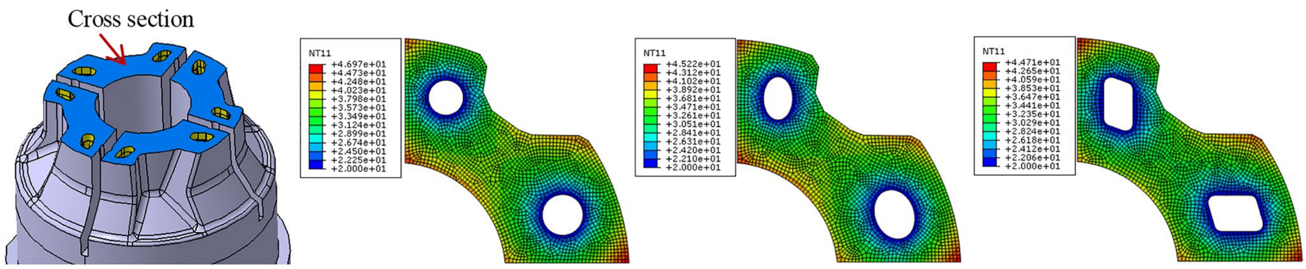

Fig. 7 Optimization of the cross section of the cooling channel in the plane parallel to the bottom of the mold core

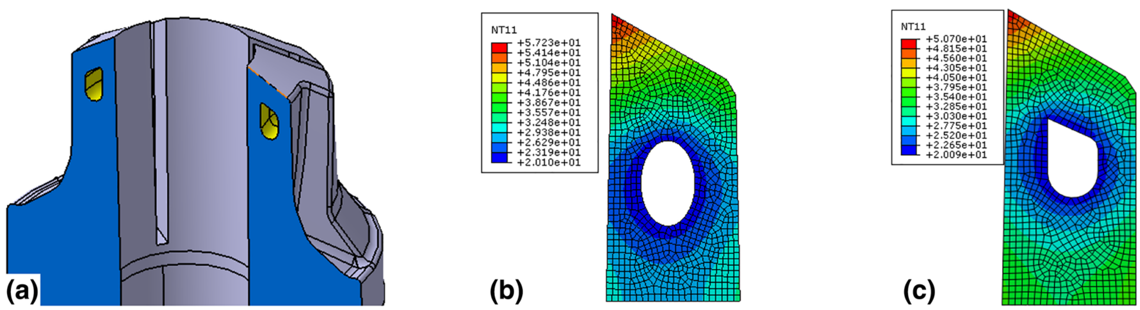

Fig. 8 3D sectioning of the mold core (**a**) with an ellipse shape (**b**) and water drop shape (**c**) of cooling channel

The optimized conformal cooling channels were made of maraging material with low thermal conductivity. The simulation result in Fig. 9 shows that the maximum temperature in the mold core was reduced to 55.0 °C and the average mold core temperature was 44.2 °C after 11 s of cooling time. In addition, the mold temperature was distributed evenly over the entire mold core surface. These simulation results indicate that the cooling time was reduced more than 50%, compared to the previous maximum mold temperatures of 80.7 °C (see Fig. 5) and 55.0 °C (Fig. 9) with 22 s and 11 s of cooling time using conventional and conformal cooling channels, respectively. Thus, the cooling efficiency of this optimized conformal cooling channel was very high.

To verify this optimized design and demonstrate the maximum efficiency of the conformal cooling channels, the mold core was fabricated by the SLS 3D printing method and two actual complete molds were manufactured, as shown in Fig. 10. The mold with the conventional cooling channels was made of KP-4M material, and the one with the conformal cooling channels in the insert core was made of maraging steel. To save the mold-making cost, the two molds differed only in their insert cores; the mold base, cavity plate, and other components were the same.

4 Experimental Results and Discussion

The experiment was done on an LGE-110 electric injection machine, and the mold with conformal cooling channels was tested first. The process parameters were set at the recommended values in Sect. 3. To ensure that the molding process reached steady state, 20 shots were made before measuring the mold temperature and checking the quality of the molded part (Fig. 11a). A digital thermal meter was used to measure the temperature at the top region of the mold core (Fig. 11b). The cycle time was set at 27 s in the machine, of which the injection time, and the mold opening and closing time were 2 and 12 s, respectively; therefore, the cooling time was 13 s. After the molding process reached steady state, the mold surface temperature was measured when the molded part was just ejected. The temperature of the mold core surface was measured as 41.2 °C, indicating that the mold temperature was low enough in the recommended range of mold wall temperatures. The quality of the product (assessed by warpage, distortion, and appearance) was very good (Fig. 11c).

When the mold with the conventional cooling channels was run, the cycle time had to be 56 s to obtain the same

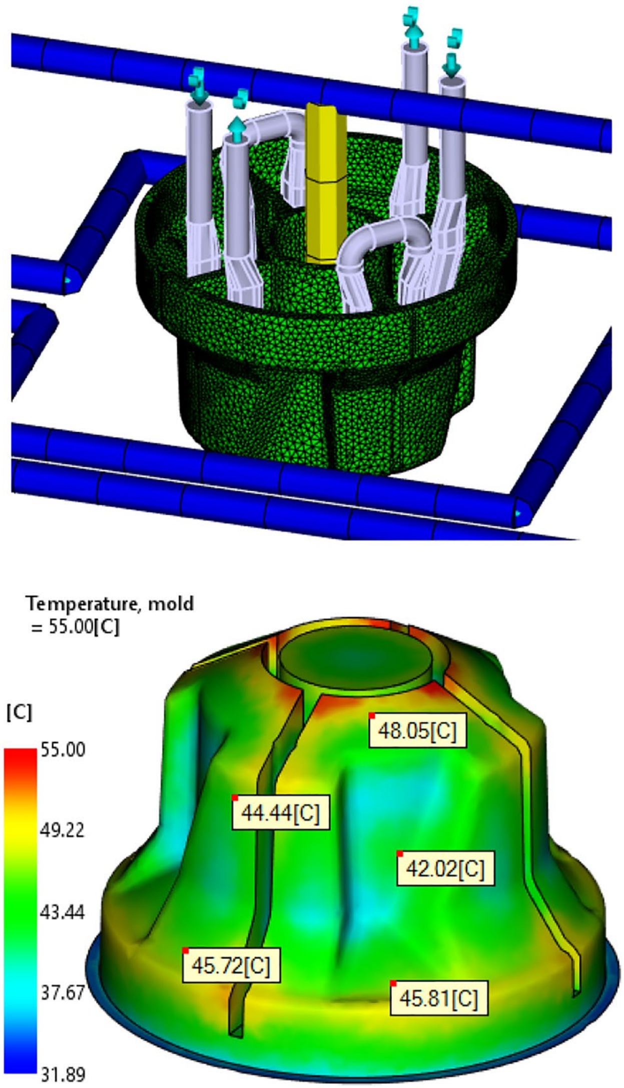

Fig. 9 Simulation result showing the even temperature distribution in the mold core when using the conformal cooling channels

part quality as that molded with the optimized conformal cooling channels. The mold opening and closing times were the same in both cases, meaning the cooling phase lasted 42 s. The mold surface temperature was measured as 68.0 °C immediately after the ejection phase; this was 26.8 °C higher than that of the conformal cooling channels. It can thus be seen that the cycle time cannot be reduced. When the mold temperature at the end of the ejection phase was 68.0 °C, the average mold temperature during the cooling phase may come nearer to the ejection temperature. As a result, the required time for solidification was increased. If we removed the molded part after 28 s of cooling time, the mold temperature was measured as 80.5 °C and the molded part was not completely solidified, as shown in Fig. 12b.

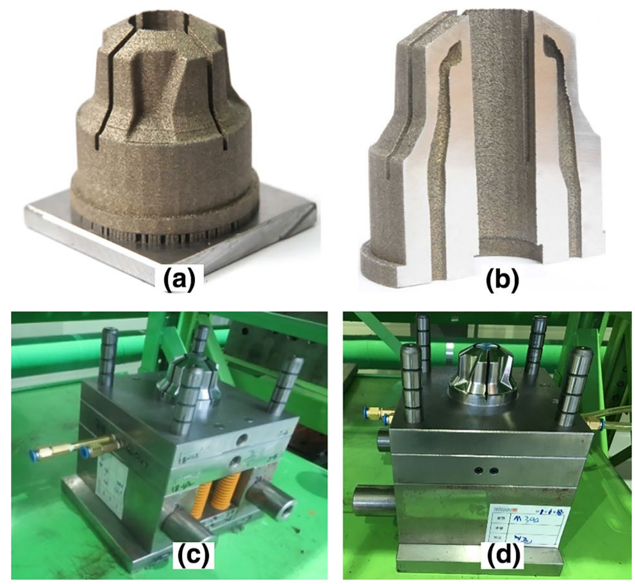

Fig. 10 The mold core made by SLS 3D printing technology (**a**), cooling channels inside the mold core (**b**), the mold assembly for the mold with conventional (**c**) and conformal cooling channels (**d**)

When these experiments were conducted, the ambient temperature was much higher than the simulation conditions due to the hot summer weather. This actual condition resulted in a higher mold temperature than that of the simulation; therefore, the actual cooling time was longer. However, as shown in the graph in Fig. 2, when the mold temperature changes only slightly in the low range of the mold temperature (e.g., from 45 to 50 °C), the cooling time theoretically increases by just about 1 s. Therefore, the slight error of the cooling time cause by the difference in ambient temperature was acceptable.

It should be noted that there were differences between the simulation and the experiment because the simulation model could never be absolutely identical to the physical model due to some simplified assumptions and differences in material properties. Nevertheless, the experimental results agreed well with the simulation (Table 1). The cooling time in the simulation was 11 s and the maximum mold temperature at the end of the cooling stage was 44.2 °C. In the experiment, the cooling time and maximum mold temperature were 13 s and 41.2 °C, respectively. It is reasonable that when the cooling time was increased, the mold temperature decreased. Therefore, the simulation and the experimental results agreed well.

The experimental results show that the cooling time reduced from 42 to 13 s (approximately 69%) when changing from the conventional to the conformal cooling channels for this case study, and the cycle time decreased from 56 to 27 s (approximately 52%). This is a significant benefit of

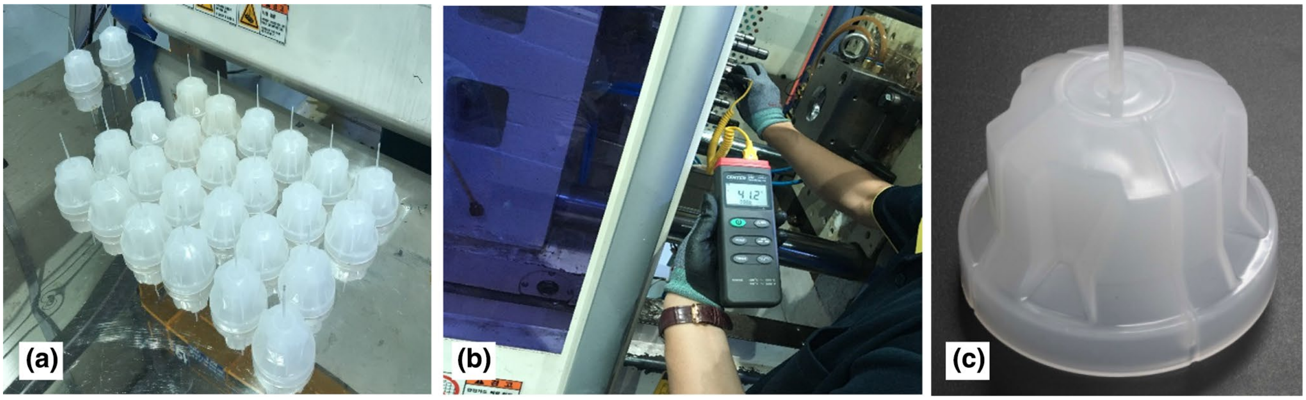

Fig. 11 The molding shots (**a**), mold temperature measurement device (**b**), and molded part with good quality (**c**)

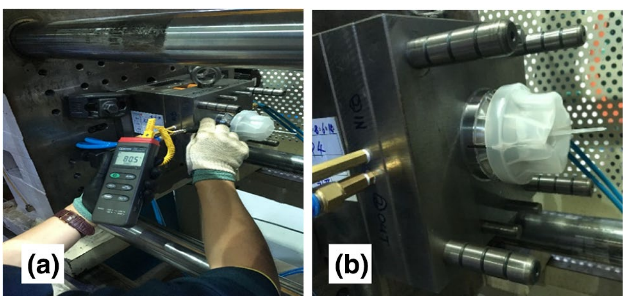

Fig. 12 Mold wall temperature (**a**) and defective molded part (**b**)

Table 1 Comparison of simulation and experimental results

	Simulation	Experiment
Cooling time (s)	11	13
Maximum mold temperature (°C)	44.2	41.2

conformal cooling channels used in injection molding, as reduced cycle times also reduce the energy and manufacturing costs.

In this work, only one case study was carried out due to the high experimental cost, including mold and tooling costs. Therefore, our result of more than 50% cycle time reduction cannot be generalized for all cases of using conformal cooling channels for injection molds. As previously mentioned, the potential for cooling time or cycle time reduction depends on the complexity of the molded part. In addition, use of conformal cooling channels requires experienced designers as well as the systematic procedures of design and optimization that have been presented in this work. The technical benefits of conformal cooling channels made by 3D printing have been proven here, and with properly designed and optimized conformal cooling channels in injection molds, more than 50% reduction in cycle time can be achieved.

5 Conclusions

This work presents the application of conformal cooling channels made by selective laser sintering technology (3D printing). The design optimization method, in terms of improved cooling performance and manufacturability, was based on analysis of the relationship between the cooling system and cooling time as well as the possibility of minimizing the cooling time. To optimize the conformal cooling channels and minimize the cooling time, the combination of analytical formulas and a simulation tool should be used. It can be concluded that a conformal cooling system always performs better (shorter cooling time and more even distribution of mold temperatures). However, the benefits of conformal cooling channels are maximized only when a systematic design optimization method is carried out. Also, the possibility of minimizing the cooling time depends on the geometry of the molded part. The more complex the core mold, the more difficult it is to cool by conventional cooling channels, and the greater the potential for cooling time reduction with conformal cooling channels. For the case study in this work, the cooling time and cycle time were reduced more than 50% compared to conventional cooling channels. This a great benefit of the design optimization and the application of the conformal cooling channels made by 3D printing.

Although the design and optimization methods proposed here practically improved the performance of the cooling channels and increased the productivity of the injection molding process, this is still a complex undertaking that requires computing skill and engineering experience of the mold designer. Hopefully the future will bring a complete computer program that facilitates the design and optimization of conformal cooling channels, and more molding case studies will be researched in support of their benefits.

Metal 3D printing is still expensive and time-consuming for large molds; therefore, the consideration of manufacturability, tooling costs, and the technical as well as economic benefits of conformal cooling channels made by 3D printing should also be further studied. Another interesting research topic is artificial intelligence control of smart and advanced mold systems, wherein the mold temperature is partially controlled by the cooling system and the process parameters are adaptively adjusted to ensure quality consistency and achieve energy savings.

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