

Establishing Design Method for Mold Temperature Control Piping of Rapid Heat and Cool Molding Used for Fabrication of High Strength Exterior Resin Parts

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ABSTRACT

Assuming the mass production of good appearance and high-strength plastic parts to be used on motorcycles, we studied the Heat and Cool (H&C) molding method to fabricate low-cost glass fiber reinforced polypropylene parts. In order to satisfy both molding cycle time and mold surface temperature uniformity requirements when temperature control piping are laid along a three-dimensional surface of a mold cavity, we used actual measurements made on test pieces to systematically define basic specifications for the piping arrangement. In addition, to deal with portions where an ideal piping design cannot be made, we developed a heat transfer simulation method that can effectively determine the surface temperature distribution of a mold cavity. With this, for a system that uses saturated steam from a boiler as the heating medium, it was indicated that a simple method to assume hot water for the heating medium can in fact be quite useful.

1. Introduction

Motorcycles are widely used in a number of Asian countries, including China, India, Thailand, Indonesia, and Vietnam, where they make up large consumer markets that support real economic growth in these very areas. Partly as a result of public transportation infrastructure not yet fully developed in these regions, motorcycles are widely used as an important means of transportation to carry both people and goods. Alongside the maturity of the market in recent years, a good appearance is becoming more desired than ever, in addition to utility needs. Accordingly, as exterior parts of motorcycles are required to have higher productivity and even greater freedom in terms of shaping, plastic parts produced by injection molding are now widely in use.

For example, rear grab rails and carriers that once used steel piping or casted aluminum to satisfy required strengths are now being produced using glass fiber reinforced plastics (GFRP). GFRP is a plastic material of which strength and elasticity are reinforced by glass fibers embedded in the base resin. While glass fibers are excellent reinforcing materials, they are prone to exposure on the surface of a molded product. Hence, it is generally not an easy task to achieve a good appearance in such products. As a result,

various efforts have been made including changing resin properties and surface coatings as a means to hide the fibers. For example, using glass fiber reinforced polyamide (PAGF) can suppress fiber exposure through altering properties of said resin.

However, optimizing the property of resin leads to higher material costs, while applying coating causes a productivity issue due to additional processes. Therefore, we opted to study the feasibility of using polypropylene as a lower cost base resin material, in order to evaluate the possibility of glass fiber reinforced polypropylene (PPGF). Generally, conventional injection molding with PPGF cannot satisfy the appearance normally required of the product. This is due to fast crystallization of PPGF that quickly solidifies the surface layer with the glass fibers exposed (see Fig. 1). To address the issue, we selected the Heat and Cool (H&C) molding method, with the intention of aiming to establish a mass production process that can satisfy external appearance requirements without the need to apply coating.

With H&C molding, a heating medium such as hot steam is used to heat the mold and then water or another cooling medium is used to cool it down during the same molding cycle. As the molding mold is heated to a desired temperature, the resin is injected in the mold to perform

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the molding. As molding is made at a high temperature of the mold, resin solidification is delayed and subsequently the characteristic of transferring the shape of the cavity is enhanced to produce mold products of excellent appearance that are free from exposed fibers or weld lines. However, by decreasing the heating and cooling cycle time in order to increase productivity, the unevenness of the mold surface temperature increases, thus leading to a poor uniformity in the external appearance, in addition to molding defects such as gas burning and burrs. As such, the issue right here was how to establish a design method that would effectively minimize any unevenness in mold surface temperatures.

In this study, to accurately estimate the mold surface temperature, we established a method using actual measurements from test pieces⁽¹⁾ and a method using simulation⁽²⁾, which are described in Chapters 4 and 5, respectively. In addition, Chapter 6 describes the effectiveness of these methods that were established using an example case of a rear grab rail.

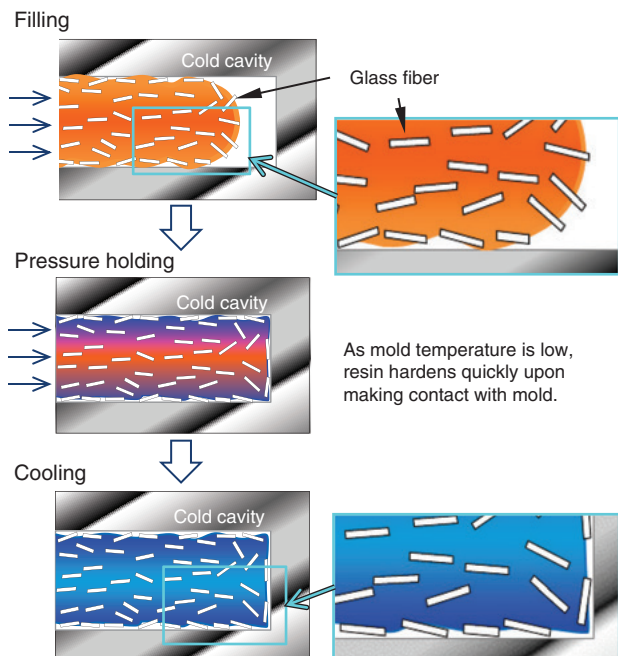


Fig. 1 Exposure of glass fibers on surface of glass fiber reinforced plastic molded by conventional injection molding

2. Setting Target Values for Molding Cycle Time and Mold Surface Temperature

While we could use induction heating, a high pressure boiler or another special mold heating system to build an efficient H&C molding system, we opted to use saturated steam from ordinary boilers that are commonly used in our

factories as the heating medium in consideration of easy deployment at other production sites. Also, according to productivity requirements, we set a molding cycle time of 120 seconds as the target value.

To evaluate the range of cavity surface temperature that can help ensure a good appearance in the product, we built a mold to produce thick test pieces that can simulate rear grab rails. The two graphs in Fig. 2 show how the surface gloss and weight of the molded PPGF part change when the cavity surface temperature is varied. The surface gloss values shown are the values measured at an incident angle of 60 degrees according to ASTM D523. This shows that a sufficient surface gloss cannot be achieved when the surface temperature is excessively low. Also, an excessive surface temperature increases contraction and reduces weight, which cause burrs and insufficient strength in the product. Accordingly, as the molding process for PPGF is required to help prevent exposure of glass fibers and to satisfy other molding quality requirements, we set a target temperature range of 120 to 145°C within which the temperature has to be controlled for the entire cavity surface.

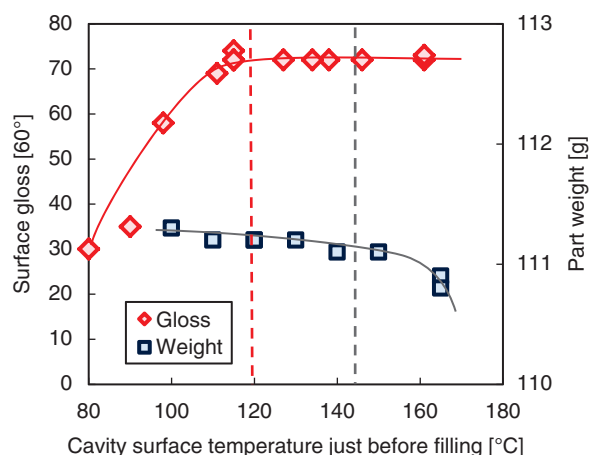


Fig. 2 Surface glossiness and weight of molded part in relation to different cavity temperatures

3. Piping Design for Three-dimensional Shaping

In order to address the issue of different surface temperatures of the mold cavity when the mold is heated, it is necessary to maintain an equal distance between the temperature control piping and the cavity surface (see Fig. 3). To achieve this, we used a “milled groove channel method” in this study to form temperature control piping by joining two blocks of molds instead of using a monolithic mold (see Fig. 4)⁽³⁾. As using this method can form the piping along the cavity surface, while maintaining an equal

distance between the piping and the cavity surface, it was felt we would be able to reduce any time lag in the surface temperature rise when the mold is heated. Also, to better track the cavity surface, we tried to minimize the diameter of the channel piping as far as possible.

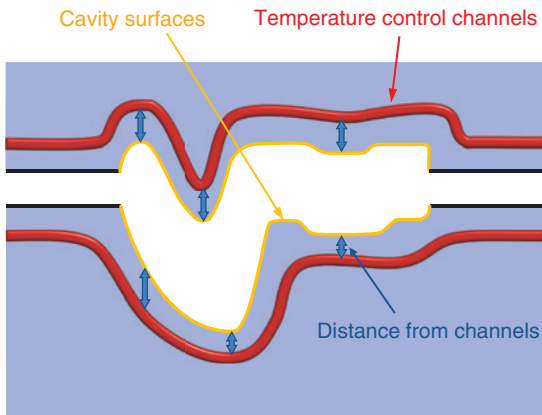


Fig. 3 Cross section of ideal Heat and Cool channels

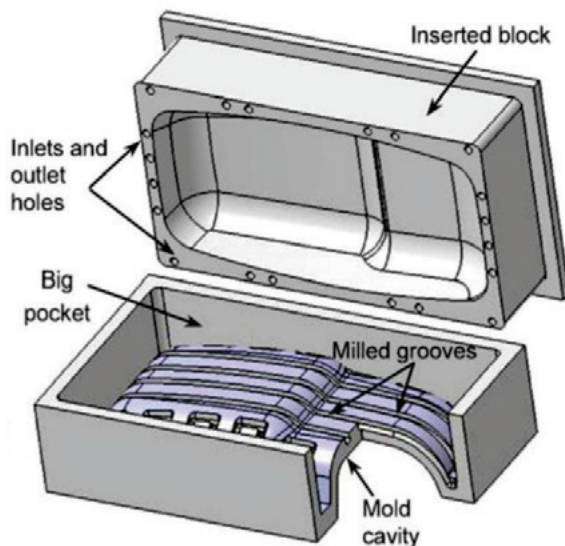


Fig. 4 Example of piping for cooling fabricated by Milled Groove Channel method

4. Defining Specifications for Mold Temperature Control System Based on Test Piece Measurements

To reduce the heating and cooling times, it is necessary to place the temperature control piping close to the cavity surface. However, if the piping is placed too close to said

surface, it may cause some temperature differences between the surface points with and without a nearby heating piping. Therefore, it is necessary to define the piping specifications in such a way that the heating and cooling can be efficiently performed, while keeping the surface temperature difference within an acceptable limit. In this, there were four major parameters – diameter (D), depth (H), pitch (P), and length (L) of the channel (see Fig. 5). By studying the behavior of these four parameters through actual measurements on a structural model that simulates the mold, we were able to establish a method to define mold temperature control specifications. These details are described in the following sections.

4.1. Channel Diameter

Although a smaller channel diameter is ideal for laying the channels along a three-dimensional surface of the mold cavity, an excessively small diameter lowers the temperature of the heating medium. Figure 6 shows how the temperature difference between the inlet and outlet ports of the test piece mold changed according to the pipe (channel) diameter in the temperature rise test when hot steam of 180°C was in use. As can be seen from the graph, the temperature difference between the inlet and outlet ports significantly increases when the channel diameter is less than 5 mm. At the same time, the channel diameter should be as small as possible as previously discussed. Accordingly, we selected a channel diameter of 5 mm for this study.

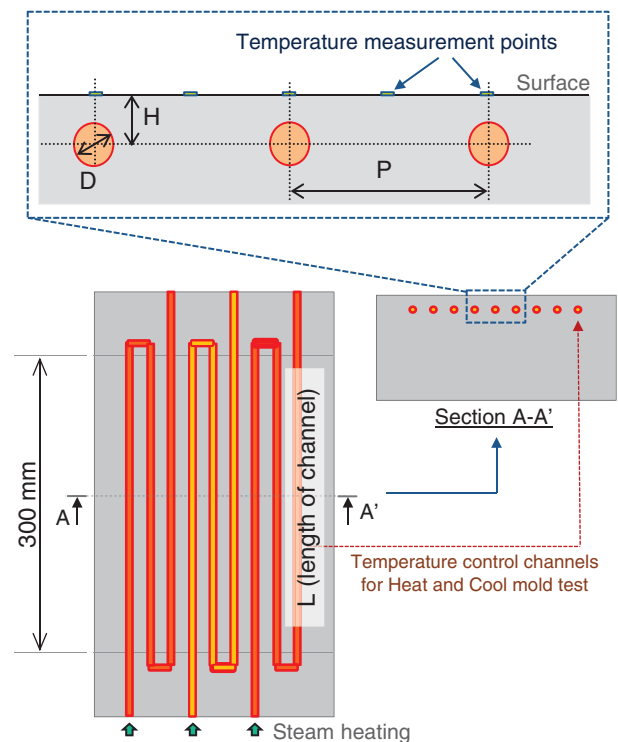


Fig. 5 Structure model of piping system for analytical investigation

4.2. Channel Depth

Figure 7 shows the relationship between the channel depth and the time required to raise the cavity surface temperature of the test piece mold to 120°C with the temperature control piping. It can be clearly seen that the smaller the depth, the shorter the heating time required. However, it should also be noted that an excessively small depth can reduce the durability of the mold. Therefore, aiming for a balance between mold durability and productivity requirements, we determined a channel depth of 10 mm for this study.

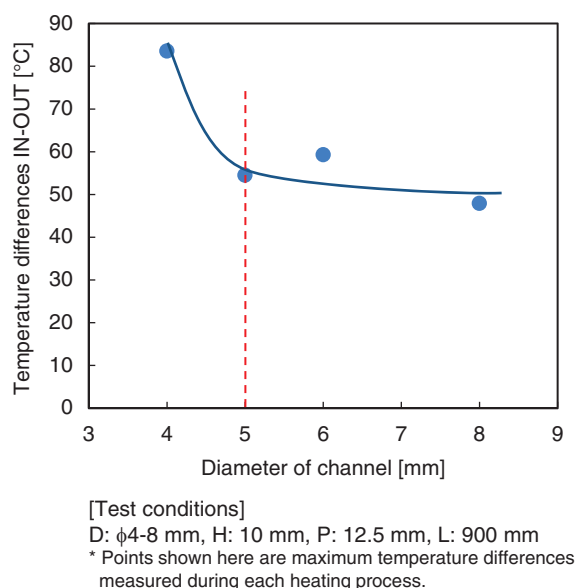


Fig. 6 Temperature differences between inlet and outlet

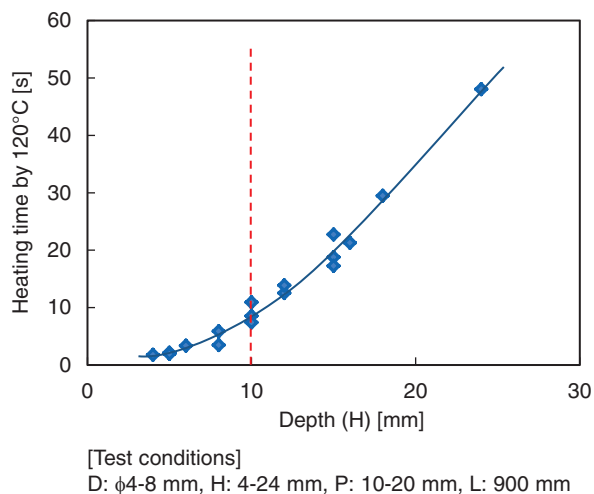


Fig. 7 Heating times to raise temperature from 40 to 120°C with different pipe diameters and pitches

4.3. Channel Length

As in the case of channel depth, we tested the temperature rise of the test piece mold by using hot steam at 180°C to determine how it was affected by channel length. While a longer channel length can ease the piping layout, the resulting temperature drop of the heating medium makes it challenging to sufficiently raise the temperature in areas near the outlet port. To find out the effects of this, we measured the cavity surface temperature of the test piece mold along the piping route. Figure 8 shows the results from this measurement. The temperature plot in this graph shows the temperature measured at each measuring point when the highest temperature among these points has reached 130°C. The horizontal axis shows the length along the channel measured from the inlet port. From the graph, it can be seen that the surface temperature starts to drop after exceeding a channel length of 1,000 mm. This suggests that the temperature of the steam in the channel is lowered in these particular areas. Based on this test result and considering that the channel length should be as long as possible as previously noted, we determined that the channel length should be within 1,000 mm.

4.4. Depth and Pitch of Channel

Following to above, we continued with the study of the depth and pitch of the channel. As shown in Fig. 9, red areas just above the channel can be easily heated up, while it is more challenging to raise the temperature in blue intermediate areas. Also, while reducing the depth can quicken the temperature rise, it increases the temperature difference between the red and blue areas. Furthermore, the resulting small thickness of the mold between the channel and cavity surface reduces the strength of the mold. At the same time, while reducing the pitch can reduce temperature differences between red and blue areas, it also reduces

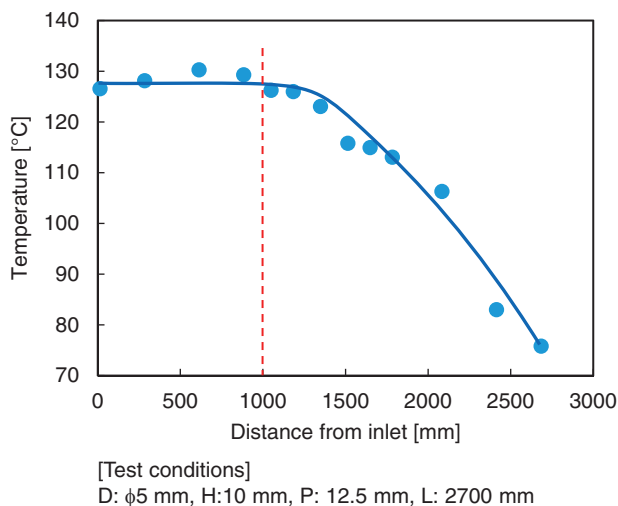


Fig. 8 Temperatures measured along channel on surface of structure model

the strength of the mold, as a direct result of the smaller distance between channels. Hence, the optimum values of depth and pitch are determined relative to each other, and its effect is presented as the temperature difference between red and blue areas, as shown in Fig. 9. We compared the temperature difference with the ratio of depth to pitch (H/P) as shown in Fig. 10. It can be seen from the graph that H/P of less than 0.5 significantly increases the temperature difference. Also, as increasing H/P decreases the temperature difference, we can uniformly raise the surface temperature to a better extent. On the other hand, the depth should be kept as short as possible in order to reduce heating times. According to the above considerations, we decided to set the ratio of depth to pitch in a range of 0.5 to 1.0. Also, as the depth was set to 10 mm based on the durability limitation of the mold as previously noted, we decided to set the pitch in the range of 10 to 20 mm.

4.5. Basic Piping Specifications Determined

As discussed above, after organizing ideas on how to minimize the heating time and temperature differences on the mold cavity surface through proper specifications for the temperature control piping, we determined the following parameters based on actual measurements: $D = 5$ mm, $H = 10$ mm, $L = 1,000$ mm or less and $P = 10$ to 20 mm (H/P of 0.5 to 1.0).

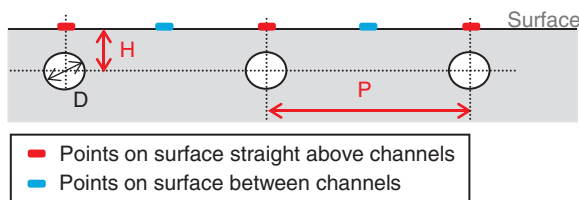
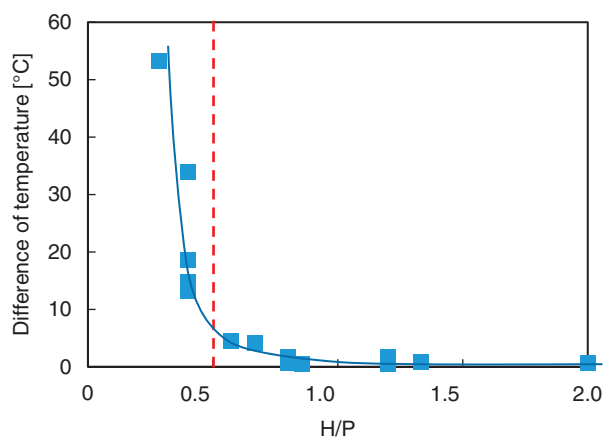


Fig. 9 Temperature measurement points on surface of structure model



[Test conditions]
H: 5-15 mm, P: 7.5-17.5 mm, $\phi 5$ mm, L: 900 mm

Fig. 10 Variation in deviations of cavity temperature in reference to ratio between H and P (H/P)

5. Simulation to Estimate Temperature Distribution on Cavity Surface

5.1. Necessity for Simulation Technology

For an actual mold design, there are portions of the mold where the temperature control piping cannot be ideally placed using the same pitch due to certain limitations caused by the use of fasteners for assembling the mold, in addition to the specific shape of a product. As such portions may not be properly heated to a desired temperature when the mold is heated, it can cause an uneven surface temperature distribution of the cavity. Therefore, unless such portions are specially treated in design, the surface temperature of the cavity could become uneven. Figure 11 shows an example of such a case. As shown by the red line, a significant temperature difference is observed at some of the temperature control points. Figure 12 shows some portion examples where significant temperature differences can be seen. As previously mentioned, the use of fasteners for assembling the mold as well as the specific shape of an actual product makes it impractical to place the temperature control piping in the same pitch as shown in the top view of Fig. 12 (a). Moreover, as shown in the cross section of Fig. 12 (b), even though the temperature control piping seem to be placed in the same pitch according to the parameter specified as viewed from the top, there can be portions where the cavity surface is more distant from the piping than at other areas. In such cases, the desired temperature distribution cannot be obtained. As such, it may become necessary to change the shape of the piping to increase the width of the channel as shown in Fig. 12 (B2) to help increase the temperature rise at these portions.

As discussed above, implementing a special temperature control piping configuration may be required at certain places in an actual mold design. Accordingly, when such a modification has to be applied, it is necessary to evaluate whether the required temperature distribution can

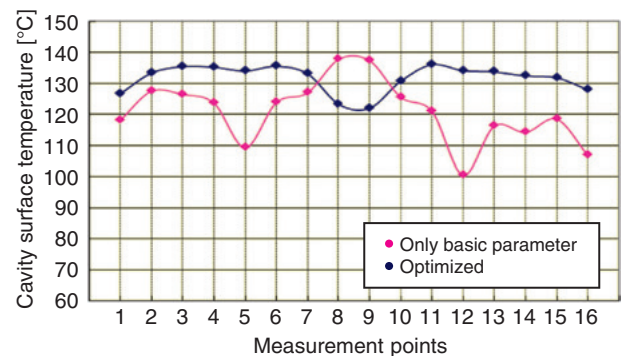


Fig. 11 Temperature distribution of cavity surface of mold for rear grab rail by optimized channel design compared with that by basic parameter channel design

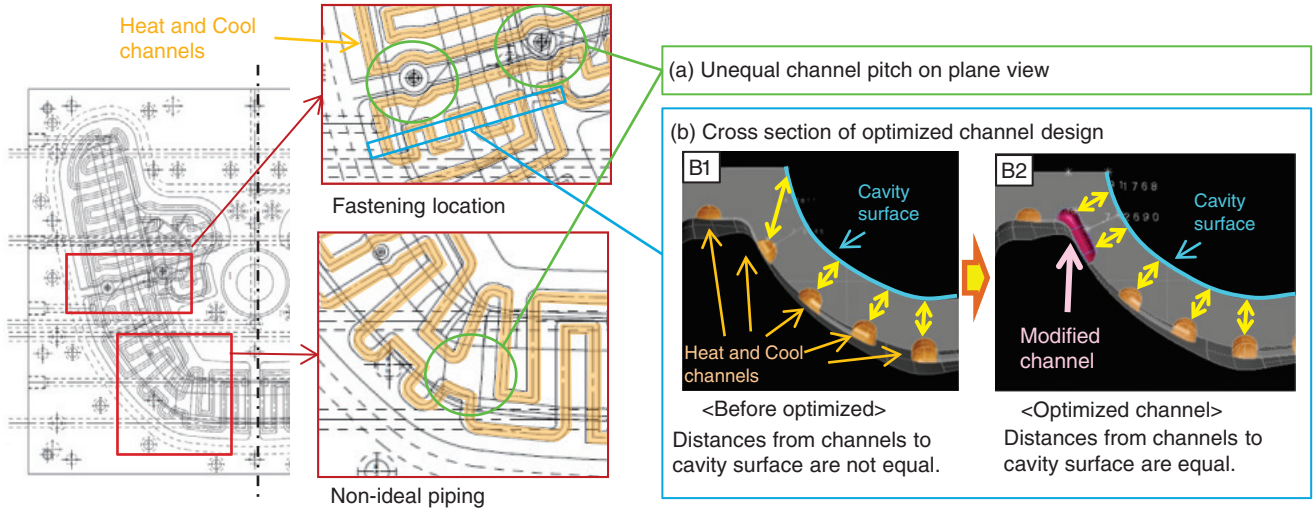


Fig. 12 Examples of non-ideal piping and cross section of optimized channel design of Heat and Cool channels

be obtained at each portion before the mold is actually manufactured. To allow for such an evaluation, we studied simulation methods that can estimate the cavity temperature distribution with the intention to make it a tool that supports a parameter-based piping design.

5.2. Simulation Method

For the temperature distribution simulation, we used 3D TIMON[®] of Toray Engineering, which is a software for plastic injection molding simulation, considering ease of use in terms of component development. We calculated the heat transfer in the temperature control piping by obtaining the Nusselt number Nu using the Gnielinski equation (1)⁽⁴⁾.

$$Nu = \frac{F_2 (Re - 1.0 \times 10^3) Pr}{1 + \frac{12.7(Pr^{2/3} - 1.0)}{1.414213562 \times F_1}}$$

$$F_1 = 3.64 \log_{10} Re - 3.28$$

$$F_2 = \frac{1}{2F_1^2}$$

$$Re = \frac{D \cdot u}{\nu} \quad Pr = \frac{\eta \cdot c_p}{k}$$

Nu : Nusselt number
 Pr : Prandtl number
 η : Viscosity
 k : Thermal conductivity
 c_p : Specific heat
 Re : Reynolds number
 D : Diameter
 u : Flow velocity
 ν : Kinematic viscosity

The hot steam used as the heating medium for the H&C molding method is saturated steam from a boiler, which is regarded as a mixture of liquid phase water and gas phase water (steam). When a heating process is initiated,

hot steam of 180°C is supplied from the boiler to the temperature control piping and is rapidly cooled by the cold water that remains in the channels. As a result, it flows as liquid-phase water in the channel (see Fig. 13).

While continuously supplying steam will replace the liquid-phase water in the channel, as the wall of the temperature control piping has a temperature lower than that of the saturated steam, the steam changes its state to liquid-phase water, as a result of condensation in the channel. Even after the liquid-phase water has been replaced by hot steam in the temperature control piping, both liquid and gas phases of water coexist in the piping, while heat transfer from the steam is made via the liquid-phase water.

From the above discussions, it was thought that the main contributor to heat transfer was water, not steam. Accordingly, we modeled the system on the assumption that hot water of 180°C is the heating medium.

5.3. Simulation Results from Test Pieces

To verify the validity of the simulation, we compared actual measurements with simulation results in relation to the surface temperature rise of the test piece. For this comparison, we modeled a test piece mold shown in Fig. 5 for the simulation. In terms of measurements, we supplied hot steam to the test piece mold as in an actual H&C molding process and measured the temperature change on the surface, which is regarded as the cavity surface of an actual mold. In addition, as the temperature control channel is defined by the four parameters of diameter D , depth H , pitch P , and length L , we produced a number of test pieces with different parameters. To verify the correlation between simulation results and actual measurements, we compared the way in which each parameter affects the heating time and temperature distribution on the cavity surface.

Figure 14 shows simulation results of the heating time

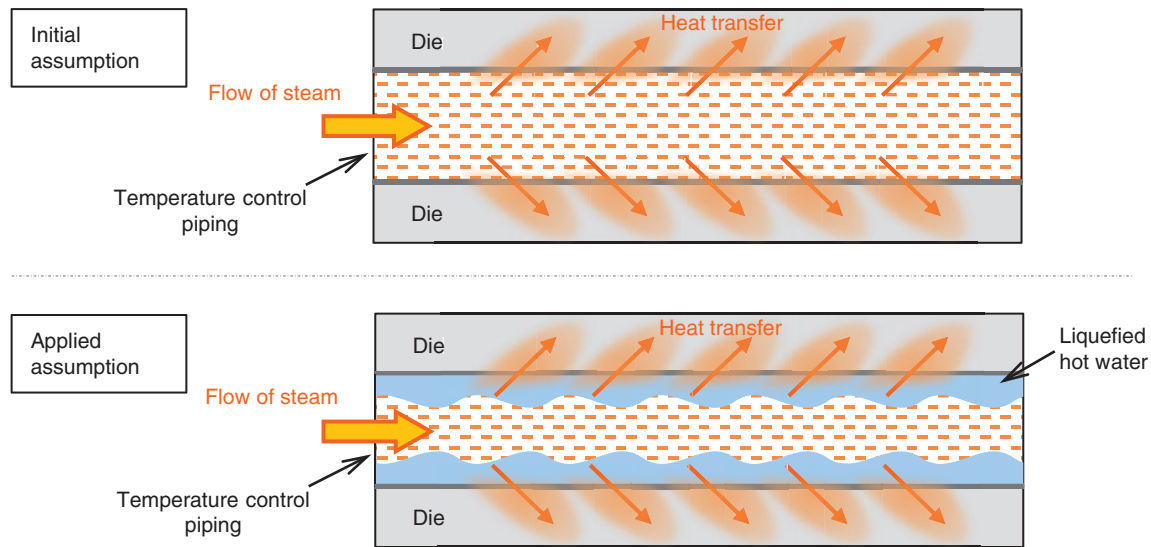


Fig. 13 Consideration on behaviors of heat medium in temperature control piping

needed to raise the surface temperature to 120°C for the values of depth H when hot water is assumed to be the heating medium. Although the heating time difference between that of the simulation and actual measurements increases at a piping depth of more than 15 mm, the simulation results are very close to the measured time at a depth H of 15 mm or less, which is mainly used in the H&C molding method. At the same time, it can be seen that the simulation assuming hot steam to be the heating medium showed a longer heating time due to a reduced amount of heat transferred to the mold, thereby failing to reproduce actual measurements. Figure 15 compares simulation results with actual measurements of surface temperature

differences at a time when the temperature reached 120°C for the depth to pitch ratio (H/P) as previously shown in Fig. 10. From this comparison, it can be seen that the temperature difference curve obtained from simulation deviates by less than 2°C from that of actual measurements for a H/P range of 0.5 to 1.0, which is the range most likely to be used in actual cases, showing that it is sufficiently accurate for temperature difference verification purposes. From these results, we determined that the simulation to assume hot water as the heating medium was practically useful for approximate analysis purposes, as it provides a robust correlation with actual measurements.

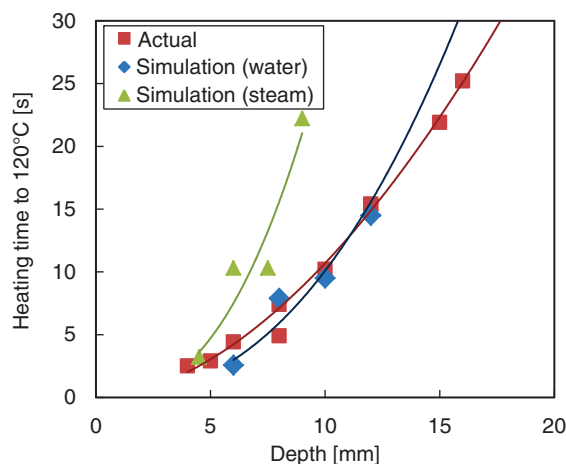


Fig. 14 Heating times to raise temperature from 40 to 120°C compared with different simulation methods

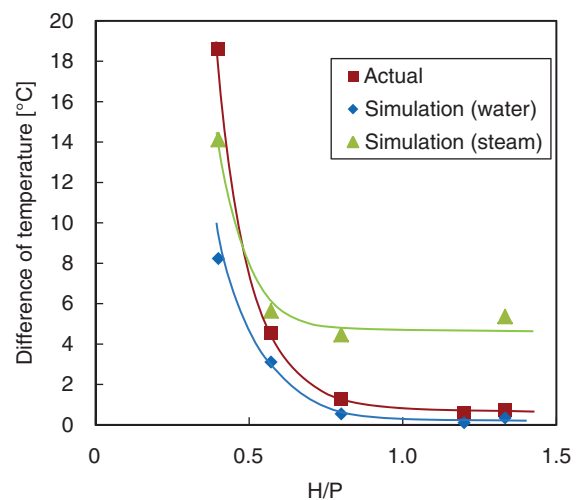


Fig. 15 Variation in deviations of cavity temperature in reference to ratio between H and P (H/P) compared with different simulation methods

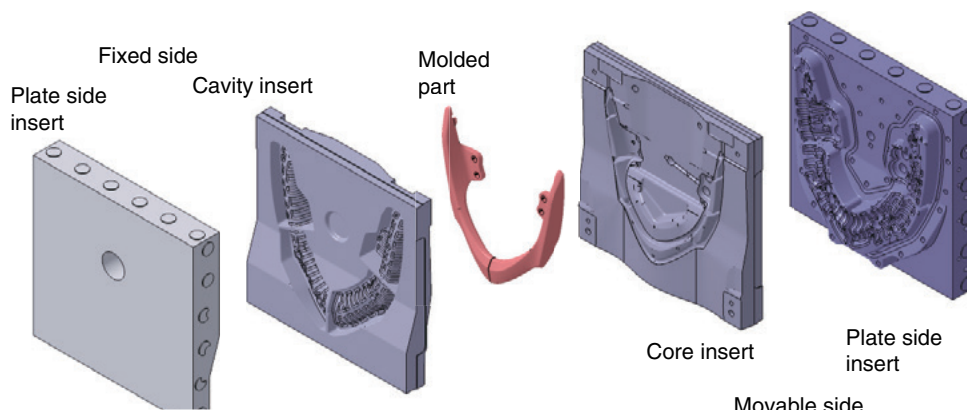


Fig. 16 Overview of mold parts fabricated by Milled Groove Channel method

6. Applying Mold Temperature Estimation Method to Rear Grab Rail

6.1. Outline of Rear Grab Rail Mold

Figures 16 and 17 show the mold structure and temperature control piping, respectively, of the mold used for H&C molding of a rear grab rail, of which piping specifications have been determined based on actual measurements with the test piece. The temperature control piping is formed in between two split mold blocks that are joined together. We provided four channels for both movable and fixed molds.

6.2. Validation

Figure 18 shows the cavity surface of the mold for a rear grab rail. The dots in the picture show measurement points. Figure 19 shows the temperature measured at

these points when the cavity surface temperature exceeds 120°C at all points. From this figure, we confirmed that all measurements were within target range of 120 to 145°C .

Also, as shown in Fig. 20, a molding cycle time of 100 seconds was achieved, which was well below the target cycle time of 120 seconds.

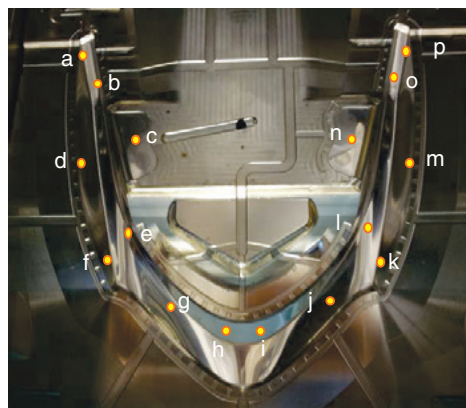


Fig. 18 Measurement points on cavity surface of mold for rear grab rail

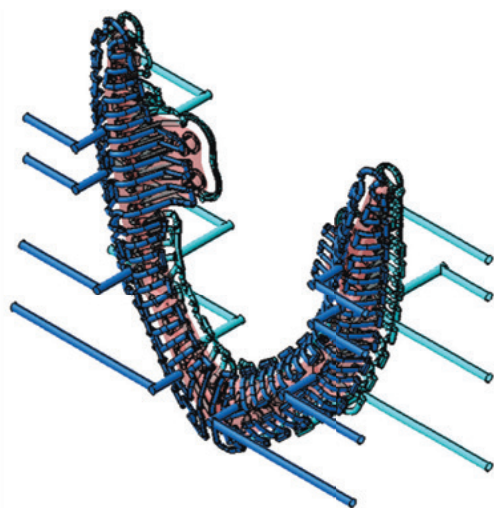


Fig. 17 Thermal control piping arrangement of Heat and Cool molding for rear grab rail mold, whose design is based on investigated specifications

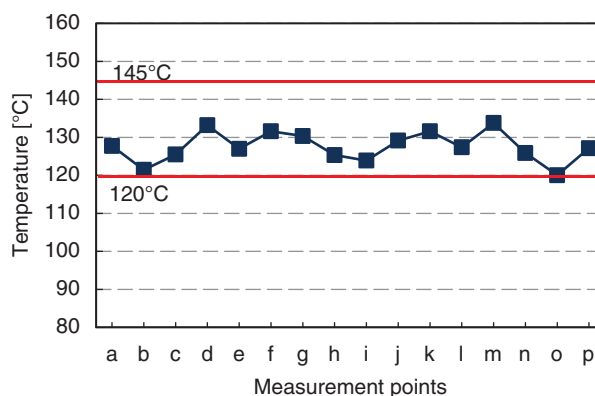


Fig. 19 Temperature distribution of cavity surface of mold for rear grab rail

Figure 21 shows external views of molded product. While exposed glass fibers are seen on the product molded with common injection molding at a mold temperature of 40°C, no such fibers can be seen on a product molded using the H&C molding method.

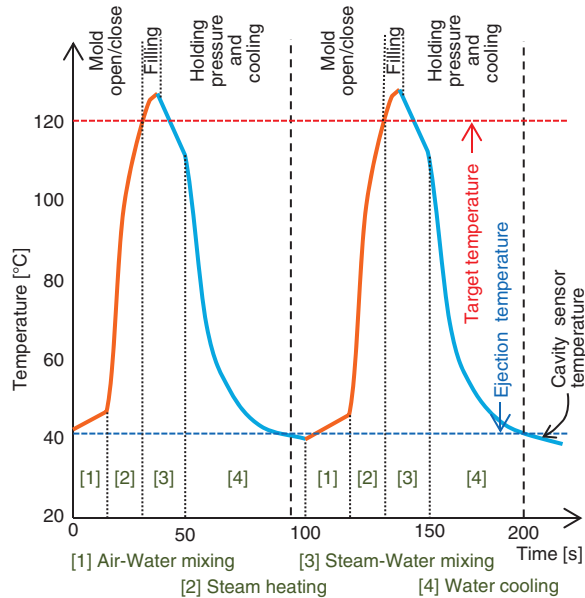
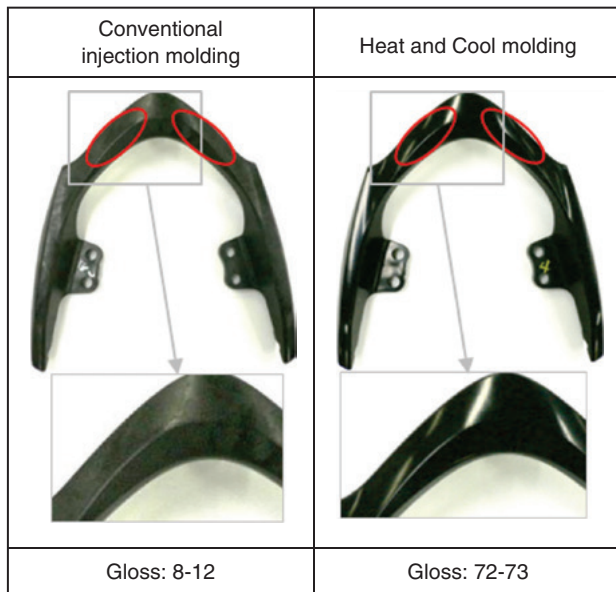


Fig. 20 Cavity temperature changes and molding cycle in actual molding processes using developed molds



○ Gloss measurement area

Fig. 21 Exterior appearances and measured gloss value of part molded by Heat and Cool method compared with part molded by conventional method

6.3. Comparison Between Simulation Results and Actual Measurements

We performed a simulation to obtain the temperature distribution on the cavity surface when a mold is heated with hot water as the heating medium. We compared the simulation results with actual measurements for the temperature distribution using the values obtained when all measurement points were at 120°C or higher. Figure 22 shows the temperature distribution obtained by the simulation together with measurement points that are used for comparison of simulation results with measurements. Figure 23 shows the temperature comparison results. It can be clearly seen from the graph that the simulation result is

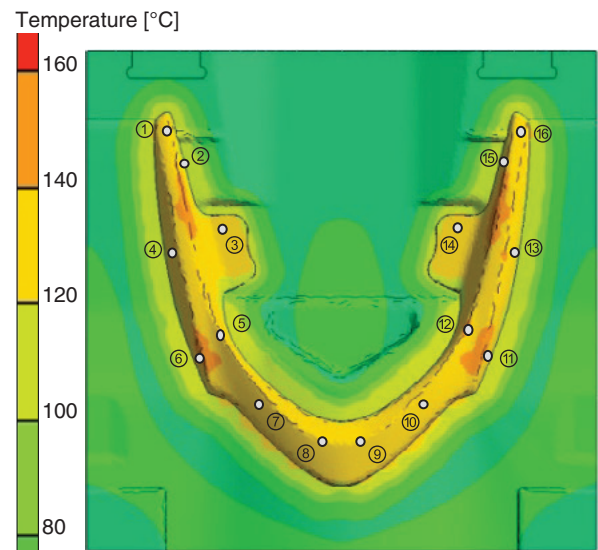


Fig. 22 Measurement points of cavity surface temperature of rear grab rail mold

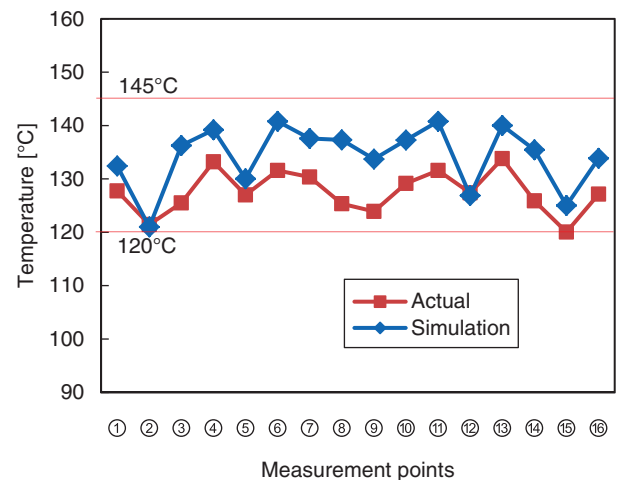


Fig. 23 Temperature distribution of cavity surface of rear grab rail mold

reproducing the trend of the actually measured temperature distribution.

When observing the entire measurement points, we can find that the simulation result has a temperature variation range of 20°C, while the actual measurement has a variation range of 15°C, which is narrower than that of the simulation. Also, separately from the above, the time it actually took to heat the mold up to 120°C was 23 seconds, which was longer than the simulation result of 10 seconds.

It can be assumed that these differences are due to the difference in the amount of heat being supplied. In the case of simulation, an ideal condition is assumed for the calculation in that hot water of 180°C is supplied to each channel at a constant flow rate. On the other hand, for an actual case it can be assumed that the amount of heat supplied is less than an ideal condition as both the temperature and flow rate may be lower than under an ideal condition. When a large size mold is used or if the boiler capacity is insufficient, it can deviate from that of the ideal condition assumed for a simulation. Accordingly, we can reasonably assume that the shorter heating time and quicker thermal diffusion of the simulation cause a trend of wider temperature distribution among measurement points than in an actual case. Therefore, although the simulation may not be useful in estimating the heating time if the capacity of the boiler is insufficient for the mold size, it is still considered to be useful in determining whether the resulting temperature distribution on the cavity surface is acceptable or not, as the simulation will act to provide a more stringent evaluation.

7. Application to Production Model

We applied the new molding method developed based on the above study results to produce rear grab rails for use on an actual motorcycle model being produced in Thailand. Figure 24 shows the actual mold used for mass production. Figure 25 shows an external view of the target motorcycle

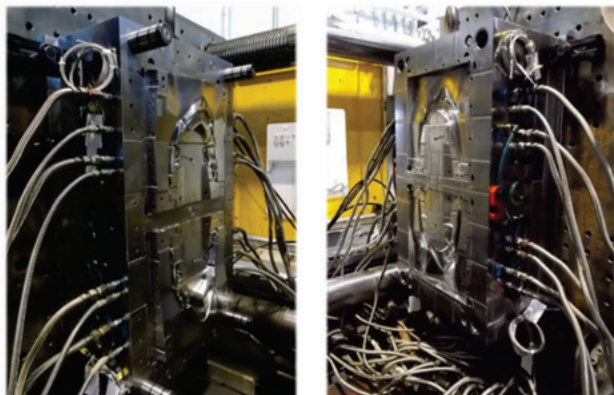


Fig. 24 Grab rail mold of Heat and Cool molding for mass production



Fig. 25 Mass production rear grab rail of Heat and Cool molding applied to Thai model

model and rear grab rail. The mold developed based on this study and used in production has achieved a production record of 400,000 shots, and an updated mold is currently in use for production.

8. Conclusion

In order to establish a technology to accurately estimate the cavity surface temperature of a mold used for H&C molding of PPGF, we established a method to use actual test piece measurements as well as a method that uses simulation. In the method using simulation, for a system that uses saturated steam from a boiler as the heating medium, we indicated that a simple method assuming hot water to be the heating medium is quite useful.

The method using test piece measurements allows for a basic design of mold temperature control piping that can evenly and quickly heat up the cavity surface.

Although the simulation method established in this study may not be useful in estimating heating time, it is still useful in terms of determining whether the resulting temperature distribution on the cavity surface is acceptable or not, as the simulation will act to provide for a more stringent evaluation. We can fully design the mold temperature control piping by additionally using the simulation, as we can estimate and evaluate the surface temperature distribution on the cavity surface even when the method based on test piece measurements cannot be applied due to any restrictions on the piping layout.

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