Paper:

Improving the Properties of Injection Molded Products with Induction Heating and Cooling Molds

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An induction heating and cooling mold that can keep the surface temperature of the entire mold cavity uniform and has a new heating and cooling insert with a gas vent mechanism is designed and produced. The effects of the temperature of the mold cavity surface, of the cavity air during the melt filling process, and of the organic gas generated from the melt on the appearance and mechanical properties of an injection molded product made of high impact polystyrene are studied. It is found that the heating and cooling mold with a gas vent can suppress molding defects, such as a weld lines and gas burns, and can greatly increase the displacement ratio of molded products obtained in the tensile test. This means that the effects of the gas vent and the surface temperature of the cavity have been quantitatively clarified using this type of mold.

Keywords: polymer, injection molding, induction heating and cooling mold, gas vent, weld line

1. Introduction

The use of the technology of injection molding in the manufacturing of electric products and automobile parts has been on the increase. However, molding defects, such as weld lines, flow marks, and silver streaks, frequently occurs in the molding process at factories. Since these molding defects degrade the appearance or mechanical properties of molded products, it has become important to prevent the molding defects. These days, products need to have good designs. Consequently, technologies [1, 2] for carving good-looking leather or wood patterns on mold cavity surfaces have been realized, and molds manufactured using these technologies are now used to make well-designed products. However in the molding process, the more complex the pattern carved on the cavity surface is, the more difficult it is to precisely transcribe it on the surface of the molded product. It is therefore necessary to develop a molding method with high transcription properties so that patterns on mold surfaces may be better transcribed on the surfaces of molded products.

When a molded product is produced, the mold is filled with the melt, which forms a fountain flow. The melt on the fountain flow front is transferred to the mold cavity surface, which is kept at a low temperature. When it touches the cavity surface, it forms a thin, solidified layer, called a skin layer, on the cavity surface [3]. It has been clarified [4] that weld lines and other molding defects occur on the molded product surface at the moment the skin layer is formed. It is therefore considered that such molding defects can be prevented if the skin layer formation is delayed and the melt is sufficiently pushed onto the cavity surface under the melt filling pressure before the skin layer is formed and the melt starts to cool. To delay the formation of the skin layer, the cavity surface temperature needs to be increased at least to the melting point T_m or the glass transition point T_g of the resin before the melt is transferred into the cavity. Unfortunately, this temperature increase means longer molding cycle times, which lower productivity. The problem is therefore how to quickly raise the cavity surface to the above mentioned temperature and then quickly lower it to the resin solidification temperature.

To rapidly heat and cool a mold cavity surface, a method [5] of circulating steam and cold water alternately in a temperature-control pipe is widely used. Also, methods [6, 7] of heating the cavity surface with electromagnetic induction-produced eddy currents and methods [8–10] using a sheath heater or cartridge heater embedded in the mold have been developed and used. In addition, a method [11] of heating resin by covering the cavity surface with a film heater and applying an electric current to the film has been proposed.

Likewise, many methods have been developed to reduce molding defects, such as weld lines, on molded products and to improve their surface properties. However, there seems to be no report of a systematic and quantitative analysis of how a changes in the cavity surface temperature affects the weld line shape, the surface properties of molded products, or the mechanical properties of molded products with weld lines or how heated cavity surfaces damage molded products. Some of the authors designed and manufactured an induction heating and cooling mold that could heat or cool a mold by means of an induction coil embedded directly in the mold and water circulated in a cooling channel in the mold [12, 13]. However, problems with the coil and the cooling channel failed to keep the temperature of the entire cavity surface

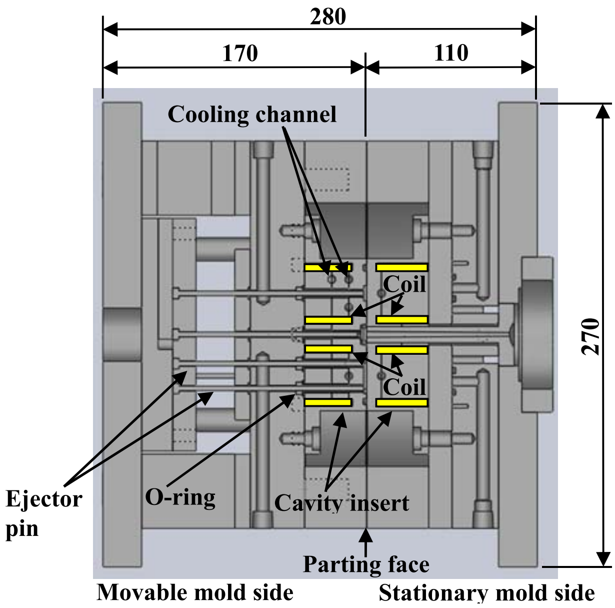


Fig. 1. Basic structure of induction heating and cooling mold (Unit: mm).

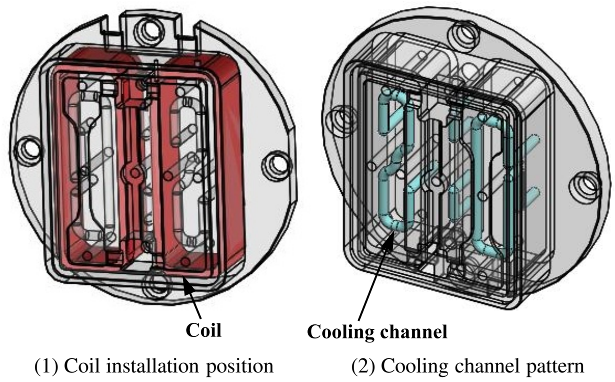


Fig. 2. Shape of cavity insert on movable mold side (Unit: mm).

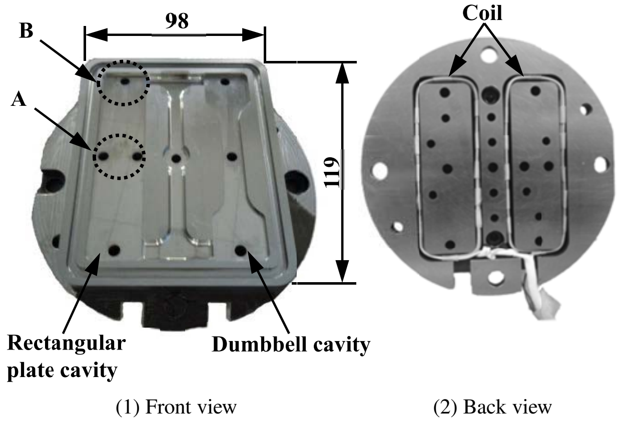


Fig. 3. Appearance of cavity insert on movable mold side.

uniform. Therefore, the effects of the cavity surface temperature and other factors on molded products could not be evaluated in an accurate way, and this was a problem.

In this study, a new heating and cooling insert with a gas vent mechanism that could uniformly control the temperature of the entire cavity surface was designed and produced. Then, an induction heating and cooling mold with the above insert embedded in it was used to study the effects of the cavity surface temperature and of the in-cavity air and organic gas emitted from melt during the mold-filling process on the appearance or mechanical properties of molded high impact polystyrene HIPS products.

2. Induction Heating and Cooling Mold

2.1. Basic Structure of the Mold

Figure 1 shows the basic structure of the induction heating and cooling mold. The heating and cooling inserts are set facing each other on the stationary and movable sides of the mold. The insert on the movable side has a cavity. That insert also has a vacuuming mechanism that utilizes a gas vent pin. From the gap between the gas vent pin, which is also used as an ejector pin, and the pinhole, air or gas is discharged from the mold. An O-ring is inserted into the joint of the gas vent pin hole to prevent gas leakage (**Fig. 1**).

2.2. Design and Production of Heating and Cooling Insert

Since a heating coil was wrapped around an insert used in previous research [12], the temperature distribution was not uniform in the direction from the outer surface to the center of the insert. This raised concerns about non-uniform deformation distribution or thermal degradation inside the molded product. Since the cooling channel position was not appropriate to the previous type of insert, the temperature distribution was not uniform in the cooling process as well. This caused molding defects such as sink marks in the molded products under some molding conditions. We therefore developed a way to set the coil for uniform heating of the insert and designed a cooling channel pattern for uniform cooling of the insert through an analysis, based on the finite element method, of heat transfer. Since the heat transfer analysis revealed a temperature difference of up to 30°C in the cavity of the previous type of the insert, the new insert was designed that would limit the temperature difference in the cavity to a maximum of 10°C.

Figure 2 presents perspective views of the heating and cooling insert designed in this study. A coil is set inside the insert, as shown in **(1)**. A cooling channel is distributed over the three-dimensional space, as shown in **(2)**. To make coil grooves and a space for the cooling channel in the insert, the insert was sliced into three pieces, grooves for the coil and the cooling channel were made in each piece, and the three pieces were reassembled using the diffusion bonding method of laminated thin metal sheets [14].

Figure 3 shows our heating and cooling insert as it actually appears. **Fig. 4** shows the appearance of the mold

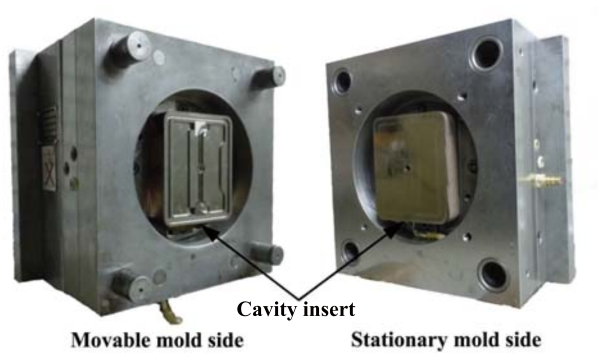


Fig. 4. Appearance of induction heating and cooling mold.

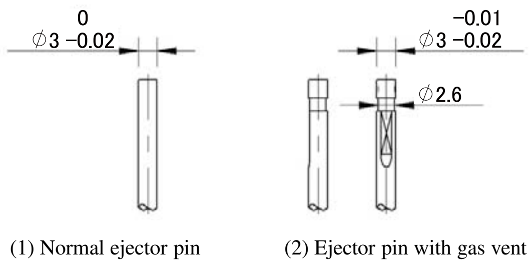


Fig. 5. Shape of ejector pins (Unit: mm).

when the heating and cooling insert is embedded in a mold base. The existing insert has a gas vent, a slit, on the parting face of the mold. On the other hand, the present insert has a structure that allows the air in the cavity and the organic gas of the melt to be discharged from a small gap between the ejector pin and the ejector pin hole, seen as points A and B in **Fig. 3**. **Fig. 5** shows the structure of the ejector pin head used in the experiment. The ordinary pin in **(1)** and a gas vent pin with a head slightly smaller than that of the ordinary pin were both used.

3. Evaluation of Temperature Increase and Decrease Characteristics of Heating and Cooling Insert

In order to evaluate the temperature increase and decrease characteristics that the insert exhibited when it was heated or cooled, a sheathed thermocouple was attached to points A and B of the heating and cooling insert on the movable mold side, and then the temperature of the points was measured. For the induction heating, a stationary induction heating unit (SK-NF002SA; Ju-OH, Inc.) was used. For cooling, a mold temperature controller (TA-32; STOLZ Co., Ltd.) was used.

Figure 6 shows the profiles of the temperatures measured at points A and B. The heating and cooling insert was heated from 50°C to 180°C and then cooled to 50°C. The profiles show that the temperature difference between A and B was smaller than 7°C. However, since uniform heating and cooling of the cavity was given priority, the temperature increase of 50°C, i.e., from 50°C to 100°C, took about 90 seconds, a relatively long time.

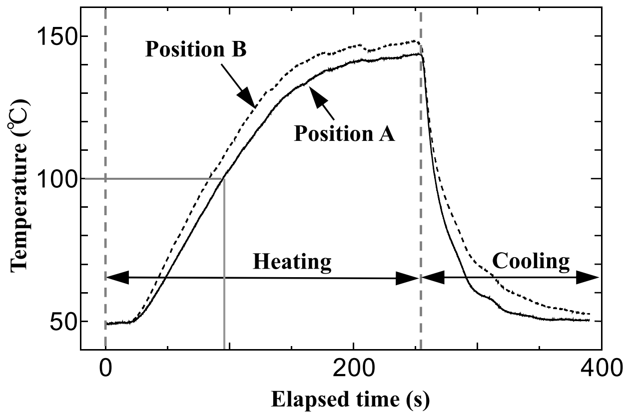


Fig. 6. Profiles of temperature inside cavity.

Table 1. Molding conditions.

Cylinder temperature*	(°C)	220−230−230−210−50
Cavity insert temperature	(°C)	40 40 → 90 → 40 40 → 110 → 40 40 → 130 → 40
Set-up injection rate	(cm^3/s)	26.5
Holding pressure	(MPa)	80
Pressure holding period	(s)	8

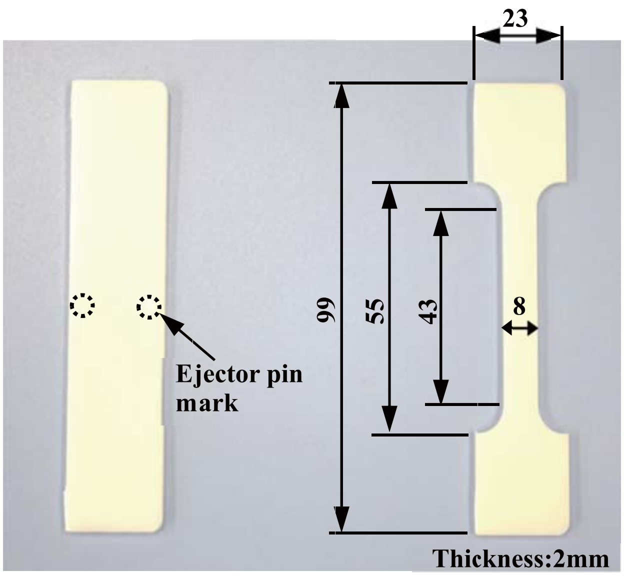
*Nozzle-Metering zone-Compression zone-Feed zone-Hopper

4. Molding Experiment

4.1. Methodology

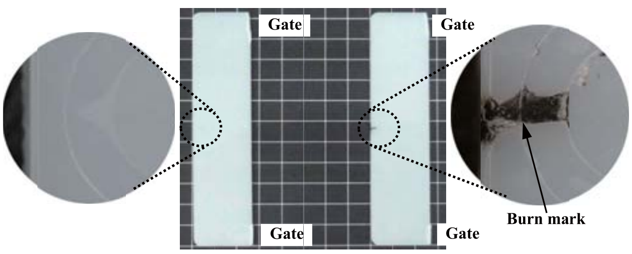
In this study, normal molding with no induction heating or cooling and molding with heating and cooling were both performed. The injection molding machine used in the experiment was a ROBOSHOT S-2000 i50A (Fanuc Ltd.) with a maximum clamping force of 500 kN. For the cavity, the rectangular plate cavity (99 mm L × 23 mm W × 2 mm D) shown in **Fig. 3(1)** was used. For the resin, high impact polystyrene HIPS (433; PS Japan Corp.) was used. **Table 1** shows the molding conditions. The normal molding was done at a constant mold temperature of 40°C; the heating and cooling molding was done by heating the insert from 40°C to 90°C for the injection and then cooling it to 40°C. This temperature cycle (denoted as 40°C → 90°C → 40°C hereinafter) and two other cycles, 40°C → 110°C → 40°C and 40°C → 130°C → 40°C, were used for the molding. To study the effects of the gas vent, normal molding using an ordinary pin and gas vent molding using a gas vent pin (**Fig. 5**) were performed. In the gas vent molding, the remaining gas in the mold and organic gas were forced out with a vacuum pump (YM-100CS; ULVAC, Inc.). The suction of the vacuum pump was set to 400 Pa.

In this study, the appearance of the molded product was observed with a 3D laser microscope (VK-9700; Keyence Corp.). A tensile test was done to evaluate the mechani-



(1) Before processing (2) After processing

Fig. 7. Shape of test piece for tensile test (Unit: mm).



(1) With gas vent (2) Without gas vent

Fig. 8. View of surface of molded products (40°C → 110°C → 40°C).

cal characteristics of the molded products. As shown in **Fig. 7**, a product made using the rectangular plate cavity was scraped to obtain a dumbbell-shaped test piece, which was then used in a tensile test. Since the cavity had two gates, a weld line was generated around the center of the molded product. To obtain a test piece with a dumbbell shape, the dumbbell-shaped cavity shown in **Fig. 3(1)** was not used for the molding; but the rectangular molded product was scraped into the dumbbell shape. This was done because a small notch from the ejector pin on the molded product, shown by the dotted line, needed to be removed, as it might have caused stress concentration. For the tensile test, a versatile testing machine (TENSILON RTC-1225A; Orientec Co., Ltd.) with a 2.5 kN maximum load of the load cell was used. The tensile speed was set to 3 mm/min.

4.2. Evaluation of Gas Burn

Figure 8 shows the appearance of products molded using heating and cooling molding with the temperature control cycle of 40°C → 110°C → 40°C and with and without a gas vent. When there was no gas vent, a black burn mark was observed on the surface of the molded product. When there was a gas vent, no burn mark was observed. With or without the gas vent, no burn mark was observed on the molded products made using heating and cooling molding with the temperature control cycle of 40°C → 90°C → 40°C.

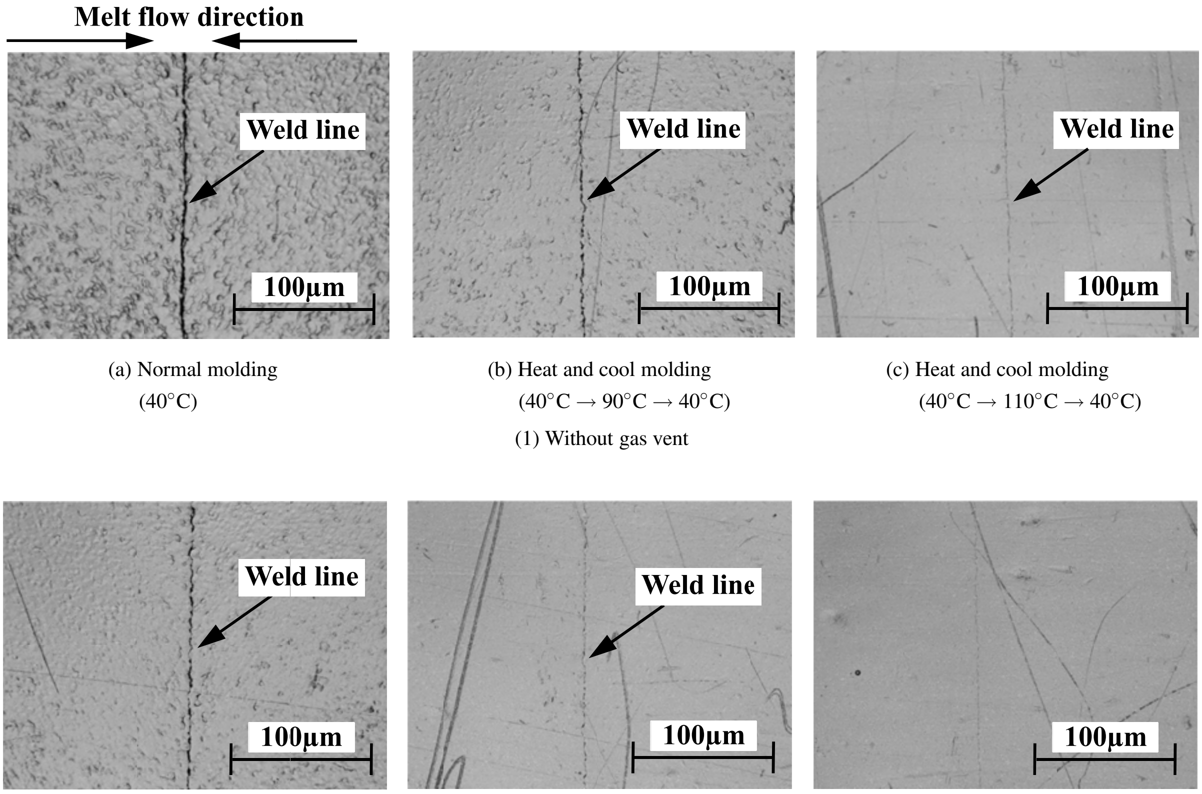
A gas burn occurred at point A in **Fig. 3(1)**, where the fronts of the two melt flows from the two gates met in the cavity. When the melt flow reached the final filling area of the cavity, the melt was able to compress the remaining air or organic gas generated from the melt. During this adiabatic compression process, the temperature of the air or gas instantly became high. It has been reported [15] that as a result, the air, organic gas, or melt contacting the air or gas has spontaneously ignited and begun burning. Some have reported [16] that the temperature of the melt flowing around the cavity surface increased with an increase in mold temperature. In heating and cooling molding with the temperature cycle 40°C → 110°C → 40°C, the temperature of the melt flowing around the cavity surface is higher than it is in normal molding. The thermal decomposition of the flowing melt thus causes organic gas to be produced. The organic gas generated in this way, the air in the cavity, and the melt are heated so until the temperature may come close to reaching the spontaneous ignition temperature. As a result, gas burn could occur more easily in a product molded using heating and cooling molding than in a product molded in the normal way.

The experiment confirmed that discharging the air and organic gas in the cavity was important to prevent gas burn, not only in the present type of induction heating and cooling mold but also in any type of heating and cooling mold.

4.3. Effects of Heating and Cooling Molding and Gas Vent on Molded Product Appearance

Figure 9 shows the appearance of the molded product at point A in **Fig. 3(1)**. The images are of products obtained by normal molding or heating and cooling molding with or without the gas vent. **Fig. 9(1)(a)** shows the appearance of the product molded by ordinary molding without the gas vent. A weld line, a V-shaped groove, can clearly be observed at the front of the flow. **Fig. 9(1)(b)** and **(c)** show the appearance of products made by heating and cooling molding. The V-shaped grooves are smaller than the groove on the product molded in the normal way, and they are even smaller when a higher insert temperature is used. The V-shaped grooves in the products made by normal molding or by heating and cooling molding with the gas vent, shown in **(2)**, are smaller than those in the products made without the gas vent, and they are almost invisible when the temperature cycle is 40°C → 110°C → 40°C.

The depth of the V-shaped grooves was measured for quantitative evaluation of the weld line. The effects of the gas vent on the relation between the depth of the V-shaped weld line groove and the temperature of the insert are shown in **Fig. 10**. In the figure, the roughness R_a of



(a) Normal molding (40°C)
(b) Heat and cool molding (40°C → 90°C → 40°C)
(c) Heat and cool molding (40°C → 110°C → 40°C)

(1) Without gas vent

(a) Normal molding (40°C)
(b) Heat and cool molding (40°C → 90°C → 40°C)
(c) Heat and cool molding (40°C → 110°C → 40°C)

(2) With gas vent

Fig. 9. Magnified images of position where melt flows meet on molded products.

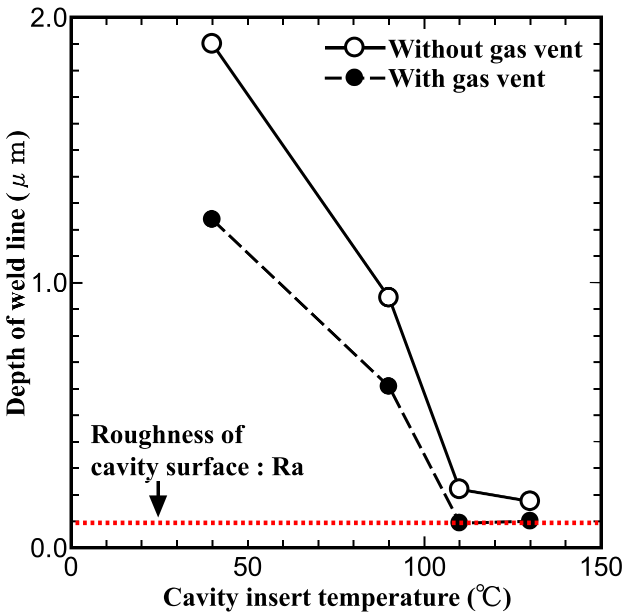


Fig. 10. Effects of gas vent on relationship between depth of weld line and cavity insert temperature.

the mold cavity surface is indicated by a dashed line. The groove depth rapidly decreases as the insert temperature increases. The depth is even shallower with the gas vent than without the gas vent. It is noteworthy that the depth almost reaches the value of the cavity surface roughness R_a if the gas ventilation is conducted at an insert temperature of 110°C or higher.

Therefore, it was found that the gas vent served to suppress the weld lines in both normal molding and heating and cooling molding. The suppression effect was particularly significant in the heating and cooling molding.

4.4. Effects of Heating and Cooling Molding and of Gas Vent on Mechanical Properties of Molded Products

Figure 11 shows the relation between the tensile stress and the displacement ratio of the molded product obtained in the tensile test. The test was conducted on 10 test pieces for each of the molding conditions, and the average values are shown in the figure. The solid line represents the data obtained without the gas vent; it indicates that the maximum tensile stress increases with the insert temperature and that the displacement ratio of the molded product is up to four times larger than that of a product molded using an ordinary method. The dashed line shows the data obtained when there was a gas vent. It indicates that the displacement ratio is up to two times larger than that of product molded using an ordinary method. The large ratio could have the following explanation. As the insert tem-

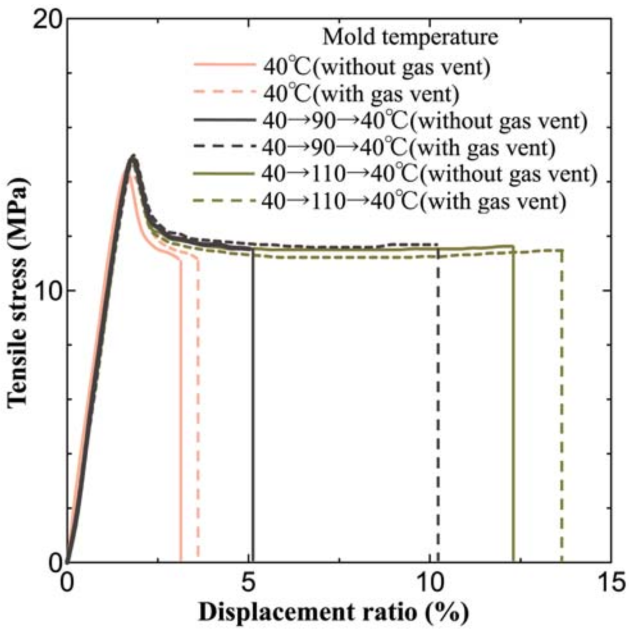


Fig. 11. Relationship between tensile stress and displacement ratio under various cavity insert temperature conditions.

perature increases, the V-shaped groove becomes smaller and the stress on the groove becomes less concentrated, resulting in the large displacement ratio observed.

In summary, heating and cooling molding with a gas vent was found to increase the displacement ratio of molded products.

5. Conclusion

The non-uniformity of the cavity temperature distribution was a problem with existing heating and cooling inserts. In this study, we designed and produced a new insert that could improve temperature distribution as well as vent gas. An induction heating and cooling mold with this insert was used to study the appearance and mechanical properties of an HIPS molded product. This study yielded the following results:

(1) It was clarified that gas ventilation could suppress gas burn in heating and cooling molding.

(2) Heating and cooling molding made the V-shaped groove of the weld line shallower. Gas venting was found to further reduce the weld line in both ordinary and heating and cooling molding.

(3) Heating and cooling molding increased the displacement ratio of the molded product obtained in the tensile test. Gas venting was also found to further increase the displacement ratio in both ordinary molding and heating and cooling molding.

We have therefore quantitatively clarified the effects of cavity surface temperature and gas venting on molded HIPS products when our mold is used. The effects of heating and cooling molding on different resins and on cavity surface properties, for example, remain to be studied in the future.

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