Effect of Gas Channel Design on the Molding Window of Gas-Assisted-Injection-Molded Polystyrene Parts

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ABSTRACT: Gas channel design plays a dominant role in determining the successful application of gas-assisted injection molding. Although empirical guidelines for gas channel design have been proposed by the various equipment suppliers, quantitative criteria based on well-designed experiments have not been reported yet. In this study, transparent polystyrene plates designed with semicircular gas channels of different radii and with rectangular gas channels of different width-to-height ratios were gas-assisted-injection-molded to investigate the geometrical effects on gas penetration with various plate thicknesses. Plate parts designed with gas channels having four different types of cross sections but with the same section area were also examined. Molding windows and criteria for gas penetration were properly chosen so that the design rule could be defined quantitatively. The moldability index was also classified into five levels (excellent, good, fair, poor, and bad) based on the relative areas of the molding windows. From a plot of the moldability index versus the ratio of the equivalent gas channel radius to the plate thickness, we found that the ratio should be approximately greater than 2 for an appropriate molding window (fair moldability index) to be obtained. The dimensional ratio of the width to the height for rectangular gas channels also affected the moldability index under the same equivalent radius. Meanwhile, for four gas channel designs, both gas channel designs attached to the top rib provided better moldability than the other designs. This investigation offers part designers preliminary quantitative design and molding guidelines for choosing an effective gas channel design that allows the parts to be molded under an appropriate molding window so that the uncertainty in both simulation and process control can be overcame. Furthermore, this study provides a methodology for the establishment of quantitative gas channel design guidelines. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 90: 2979–2986, 2003

Key words: gas channel; molding window; moldability index; equivalent radius

INTRODUCTION

Gas-assisted injection molding (GAIM) is one of the most important and innovative molding processes.[1–4] A schematic of GAIM is depicted in Figure 1. In this process, a gas is injected into a mold cavity filled partially with a polymer melt. The gas drives and penetrates the molten polymer core further into the mold until the mold is completely filled. The penetration of the gas into molten plastic is called *primary gas penetration*. Afterward, the gas continues to penetrate when the polymer melt is cooled and provides packing pressure to the polymer skin. Once the polymer skin has been completely solidified, the gas pressure is released, and the product is ejected. Gas penetration in the postfilling stage is called *secondary gas penetration*. Compared with conventional injection molding (CIM), GAIM can substantially reduce operating expenses by reductions in material costs, lowered injection-pressure and clamp-tonnage requirements, and reductions in cycle times for thick-walled parts.[1–12] In addition, some of the molding issues encountered in CIM of large parts, such as sink marks, residual stresses, distortion, and warpage may also be greatly reduced when GAIM is used instead. It also allows more design freedom for structural ribs and bosses that usually introduce sink marks and other surface appearance issues when CIM is used. Furthermore, GAIM parts have higher stiffness-to-weight ratios and better mechanical properties, including tensile strength, flexural strength, and impact values, than those of CIM parts because of reduced residual stresses.[13–19]

Although GAIM has many advantages in comparison with CIM, it introduces new processing parameters and makes the application more critical. Computer simulation[3,7,8] has become an important and required aid in part design, mold design, and process evaluation in recent years. However, fundamental studies concerning the effect of gas channel design and molding conditions on gas penetration[5–8] and part properties[10–19] are also required to build quanti-

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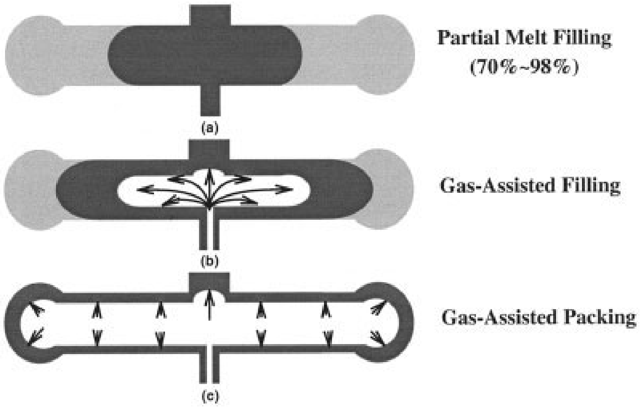
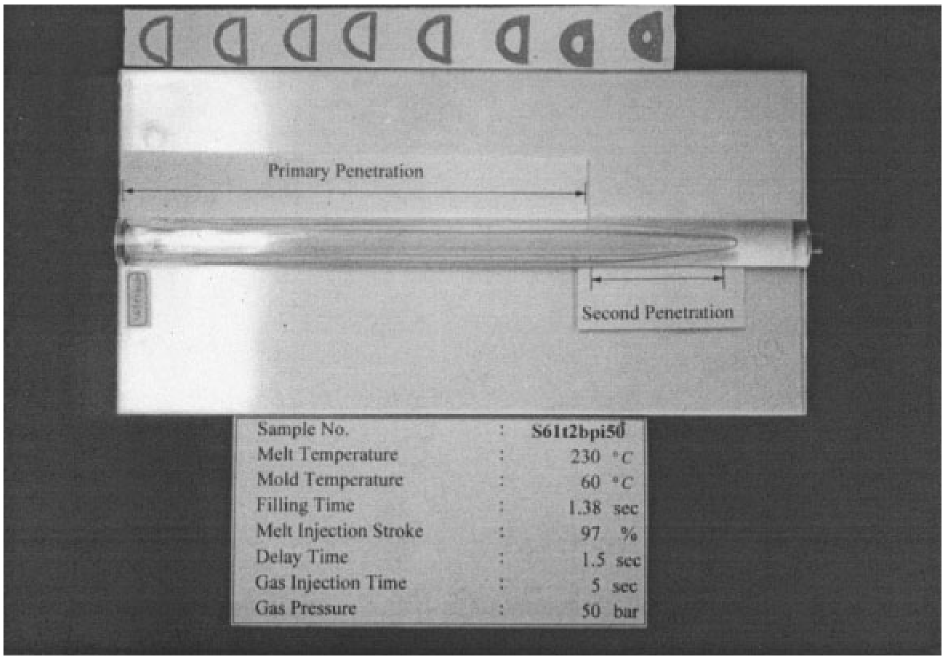


Figure 1 Schematic of the GAIM process.

tative design and molding guidelines to assist in the application of GAIM. The design of gas channels guiding gas penetration to desired locations is the most critical issue. A typical GAIM part, showing a gas channel and a hollowed core due to gas penetration, is depicted in Figure 2. Basically, gas tends to penetrate toward the direction of least flow resistance. As a result, the amount of the melt in front of the gas entry and the dimensions of the gas channel and part thickness along the flow direction will determine the characteristics of gas penetration. Oversized gas channel design usually leads to insufficient gas penetration, whereas undersized gas channels often cause lateral permeation resulting in mechanical strength weakness, as shown in Figure 3. If the layout of the gas channels and their corresponding shapes, dimensions, and cross sections are inadequately designed, catastrophe often occurs in the molded parts. In addition to the design parameters introduced by gas channels, other processing parameters, such as the numbers and locations of gas-injection points, the amount of the polymer melt injected, the delay time, the injected gas pressure, and the holding time for gas injection, are also important for obtaining good molded parts. Only when the design of gas channels and the processing parameters are well understood can the GAIM process provide its potential advantages.

Computer simulations of GAIM have been reported previously.[7,8] Although a fully three-dimensional simulation approach may be required eventually, the most popular methodology at this time is to use the shell element model superimposed with an equivalent beam element representing a gas channel (Fig. 4). Chen et al.[16] extended this processing simulation to warpage and structure performance analyses under a unified computer-aided engineering (CAE) model while using two different methods of equivalent diameter conversion for melt-flow and structural evaluations, respectively. The effects of gas channels on the mechanical properties of GAIM parts were reported.[17–20] Guidelines for the structural enhancement of gas channels were also proposed. From the viewpoint of the part designer, it is very important to have design and molding guidelines for the moldability of parts, particularly the quantitative dependence of the moldability on the gas channel shape and the associated dimensions. In a study conducted by Yang and Liau,[21] the molding windows (by means of the melt temperature vs the injection stroke) for three types of gas



Sample No. : S61t2bpi50
Melt Temperature : 230 °C
Mold Temperature : 60 °C
Filling Time : 1.38 sec
Melt Injection Stroke : 97 %
Delay Time : 1.5 sec
Gas Injection Time : 5 sec
Gas Pressure : 50 bar

Figure 2 Typical gas-assisted-injection-molded part showing the gas channel and hollowed core due to gas penetration.

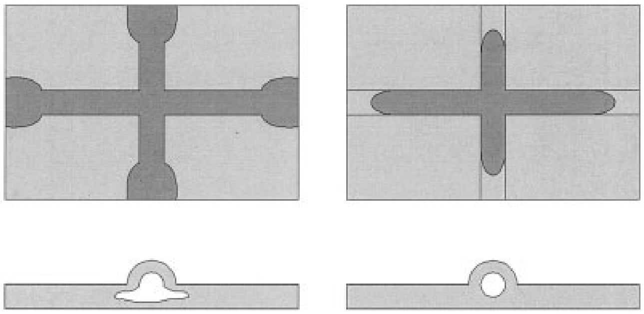


Figure 3 Schematic of insufficient gas penetration and lateral permeation with gas channels leading to improper part defaults.

channels (rectangular, trapezoid, and semicircular cross sections) with the same area were evaluated. It was found that the gas channel with a semicircular cross section provided a slight advantage over the others. From the area of the molding window, it could be seen that the semicircular cross section was larger than the trapezoid cross section, and the worst was the rectangular cross section. Although the work of Yang and Liau provided an initial step toward quantitative guidelines for GAIM part molding design, it seems that a more fundamental rule determining the molding window and the associated molding criteria is required.

In this study, quantitative design guidelines for gas channel section geometry were investigated. Plate parts of different thicknesses and gas channels (semicircular with different radii and rectangular with different width-to-height ratios) were gas-assisted-injection-molded to investigate the geometrical effects on gas penetration. Meanwhile, plate parts designed with gas channels having four different types of cross sections but the same section area were also examined. A methodology for molding window definition and criterion selection as well as the associated moldability index was proposed. Then, the channel section geometry was converted into the equivalent circular radius, from which its ratio with the plate thickness was correlated with the moldability index. Finally, from the correlation, we established design guidelines for gas channel section. Hopefully, this can help designers to choose the most effective gas channel design for suitable moldability.

EXPERIMENTAL

A 75-ton Battenfield 750/750 coinjection-molding machine and an Airmold gas-injection system with five-stage pressure profile control were used for the experiments. A plate mold, which allowed 2-mm, 2.5-mm, and 3-mm part thicknesses associated with gas channel designs of semicircular cross sections (with radii of 2, 4, 6, and 6.91 mm) and rectangular cross sections (H5W10, H5W15, H10W10, and H10W15), as shown in Figure 5, was designed to conduct the experiments. For convenient discussion, the specimens are designated by the radius of the semicircular gas channel and plate thickness or by the width and height of the rectangular gas channel and plate thickness. For example, R4T3 represents a 3-mm-thick plate with a 4-mm radius in a semicircular channel section; H5W10T3 represents a 3-mm-thick plate 5 mm high and 10 mm wide in a rectangular channel section. Alternatively, a plate mold 2.5 mm thick was also designed with gas channels having five different types of cross sections (Fig. 6). The areas under the channel cross sections were all the same (75 mm^2). These four different types of gas channels are represented as A, B, C, and D. Transparent polystyrene (PS) resin was used as the material. Transparent PS could easily be examined upon gas penetration. Preliminary studies found that the molding conditions were critical to the gas penetration length. To simplify the experimental process, after several trials, we chose 230°C for the melt temperature for the resin and 60°C for the mold temperature. The gas was introduced without a delay time. Among all processing parameters, the amount of the polymer melt injection (injection stroke) and the gas pressure are the two most important common parameters for controlling the gas penetration length. It is expected that insufficient stroke will result in a gas breakthrough, whereas excess stroke will lead to insufficient gas penetration. However, if the injected gas pressure is too high, lateral gas permeation will usually result, and short shot may happen if the gas pressure is too low

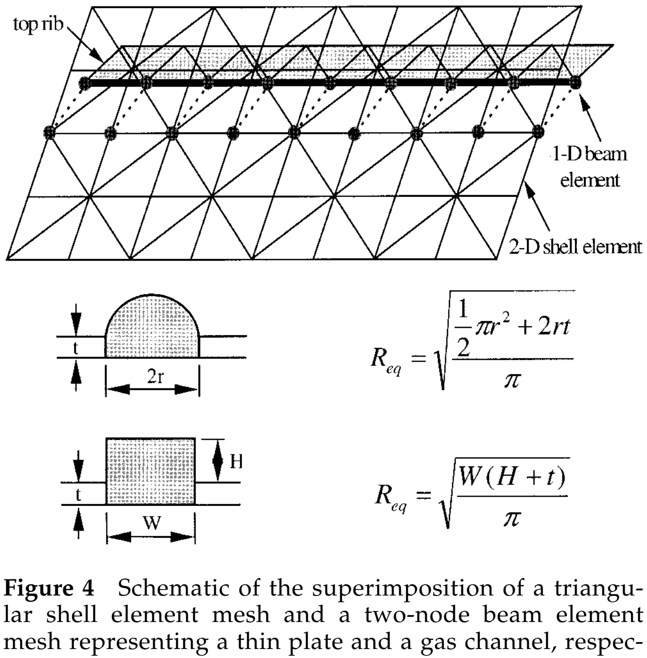


Figure 4 Schematic of the superimposition of a triangular shell element mesh and a two-node beam element mesh representing a thin plate and a gas channel, respectively.

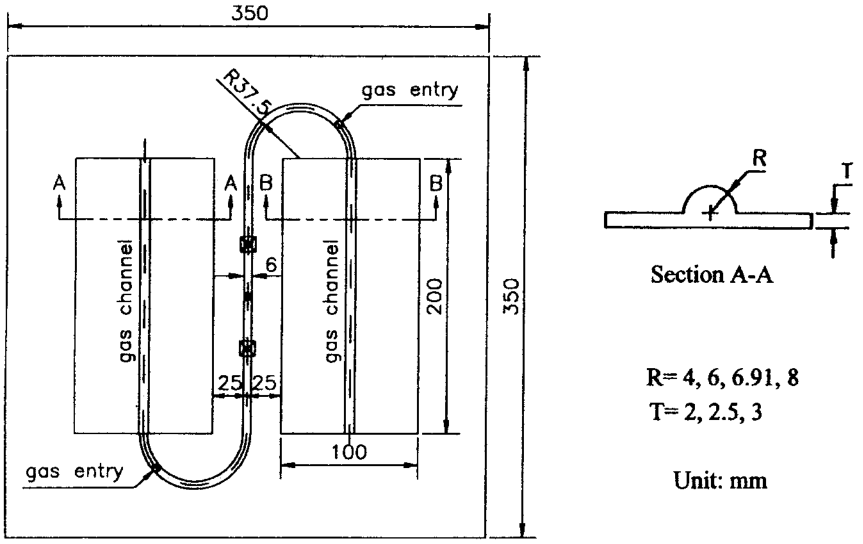


Figure 5 Mold geometry for a thin plate designed with a gas channel of semicircular and rectangular cross sections.

to push the melt to flow. Therefore, the molding window can be defined in a plot of the gas pressure versus the injection stroke (Fig. 7). In actual molding, the expected phenomenon does occur. To define the molding window more specifically, we need to choose the criteria for gas penetration.

Consequently, the moldable criteria were chosen in such a way that the gas penetration had to be over 80% (i.e., 160 mm) along the gas channel and lateral permeation had to be less than 1 mm away from both sides of the gas channel, as described by the schematic in Figure 8. The injection stroke and the gas pressure were varied to ensure that the molded parts satisfied the moldable criteria. Five samples were molded under the same processing conditions. Then, the averaged values from these measurements were used for analyses and correlations. Alternatively, for the evaluation of the effect of the channel section shape and associated dimensions and the part thickness on the moldability, the equivalent radius (R_{eq}), which is usually adopted in a process simulation to represent the size of a gas channel, was used to present a gas channel of a noncircular shape. The R_{eq} values for gas channels with semicircular and rectangular cross sections were calculated in this study as follows:

$$R_{eq} = \sqrt{\frac{\frac{1}{2}\pi r^2 + 2rt}{\pi}} \tag{1}$$

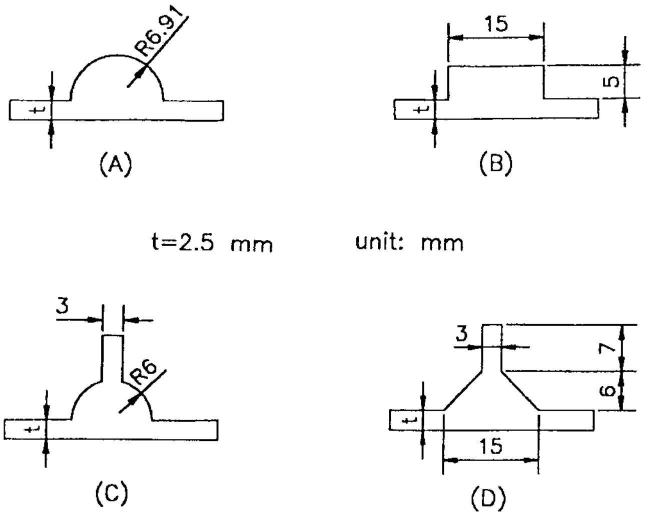


Figure 6 Gas channels of four different cross-section geometries.

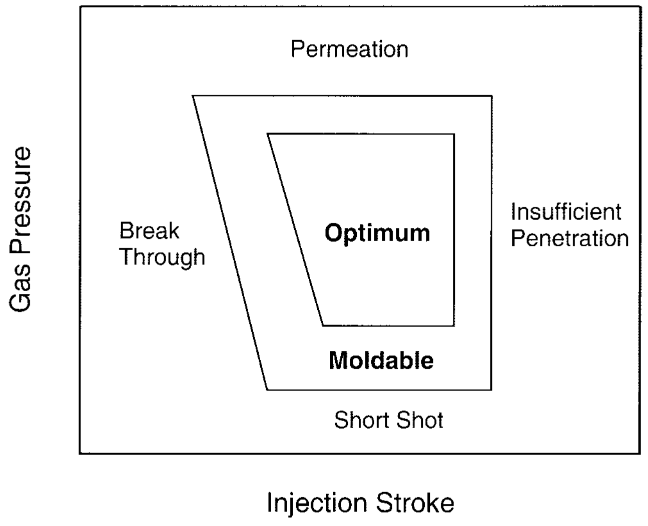


Figure 7 Schematic of a molding window represented in terms of the injection stroke and gas pressure.

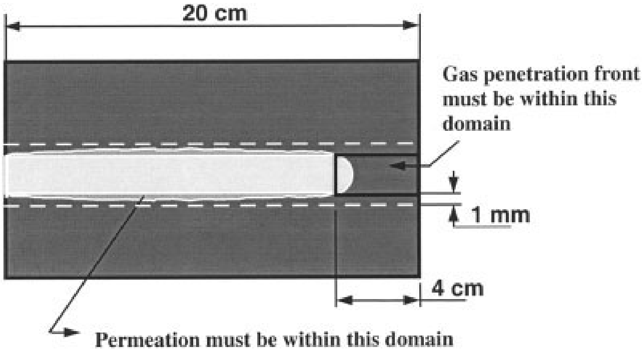


Figure 8 Schematic of the moldable criteria. The gas penetration length must be over 80% along the gas channel, and the permeation must be less than 1 mm on both sides of the gas channel.

$$R_{\mathrm{eq}} = \sqrt{\frac{W(H+t)}{\pi}} \tag{2}$$

In these two expressions, *r* is the radius of a semicircular gas channel; *t* is the plate thickness; and *W* and *H* are the width and height of a rectangular gas channel, respectively.

RESULTS AND DISCUSSIONS

Moldability of GAIM parts with semicircular gas channel design

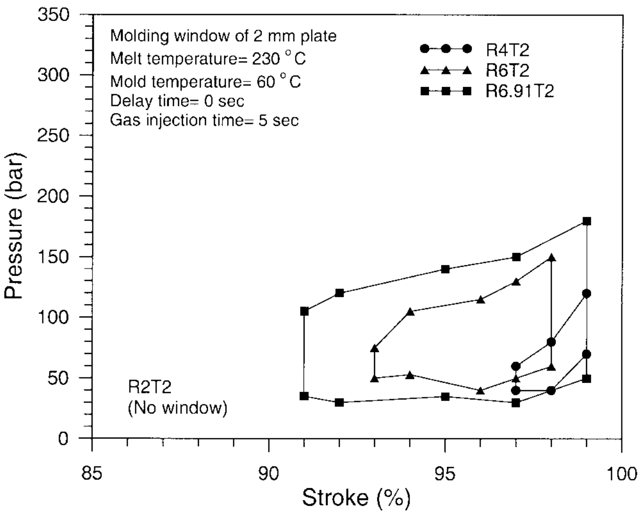


Figure 9 Molding windows for a 2-mm plate designed with semicircular gas channels of various radii.

Basically, ribs are designed in CIM parts to improve the rigidity and structural integrity. However, design limits for the height and width of ribs have been very strict to prevent the possible introduction of sink marks on the back walls of ribs. Gas channels in GAIM parts act similarly to ribs in CIM parts and may also introduce sink marks if they are not properly penetrated by gas. For plate parts 2, 2.5, and 3 mm thick, the most popular gas channel design is that of a semicircular cross section. For a plate with a semicircular gas channel 2 mm in radius, it is difficult to get a full gas penetration along the channel. It is believed that when the radius of a gas channel is too small, the gas does not have a clear path of least resistance, and so the gas tends to penetrate into the plate area; this results in insufficient gas penetration along the gas channel, and fingering may occur. Consequently, no molding window is shown for plate parts designed with gas channels with semicircular cross sections 2 mm in radius and based on the molding criteria selected. Alternatively, for a plate part thickness of 2 mm, molding windows of three different gas channels with radii of 4, 6, and 6.91 mm are represented in Figure 9. There is a tendency for the area of a molding window to increase with the increasing radius of a gas channel. As far as the molding windows for 2.5- and 3-mm-thick plates displayed in Figures 10 and 11, similar to a 2-mm-thick plate, the area increases with the increasing radius of the gas channel. In addition, the moldable conditions shift toward lower gas pressures. At the same time, the area of a molding window decreases gradually when the thickness is varied from 2 to 2.5 to 3 mm. For example, in comparison with a molding window with a gas channel radius of 4 mm, the molding window area varies from a block (of 2 mm) to a line (of 2.5 mm) to no window at all (of 3 mm). On the basis of these results, it is believed that increasing the plate thickness will lead to easier gas penetration into the thin wall area and result in unsatisfaction criteria regarding gas permeation. In addition, because of the lower flow resistance, the part favors molding at lower gas pressures.

For the comparison of the moldability for plates (2, 2.5, and 3 mm thick) designed with gas channels of

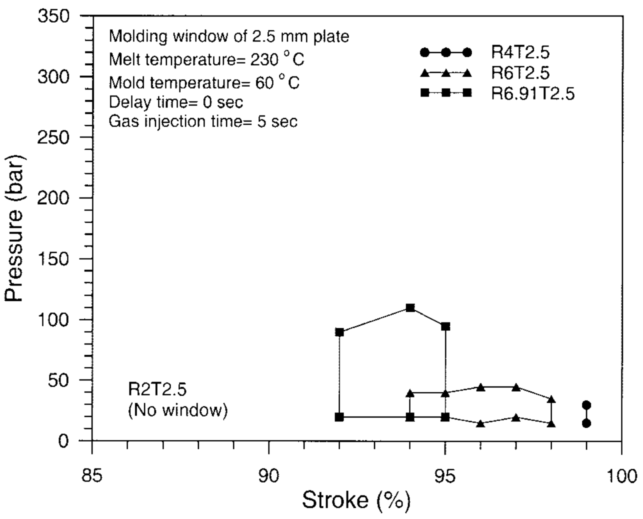


Figure 10 Molding windows for a 2.5-mm plate designed with semicircular gas channels of various radii.

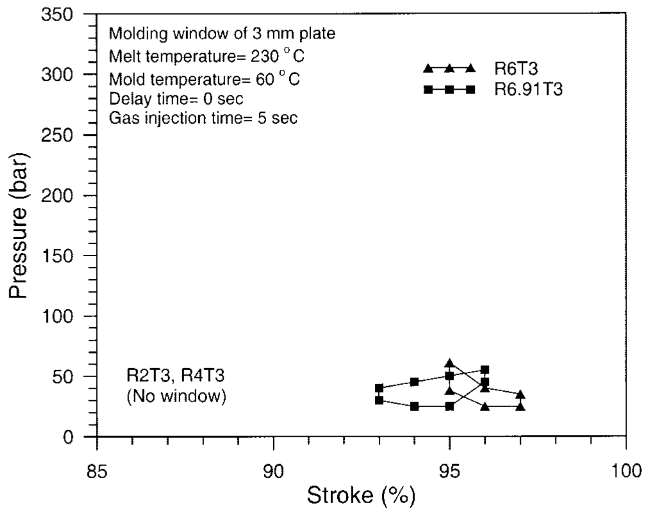


Figure 11 Molding windows for a 3-mm plate designed with semicircular gas channels of various radii.

different sizes in a quantitative way, one can define the moldability according to the relative sizes of the molding windows. Here five levels of moldability are specified under the same gas channel shape. The specified index values are 1 (bad, exhibiting no molding window at all), 2 (poor), 3 (medium or fair), 4 (good), and 5 (excellent). A larger value of the moldabilty index indicates a larger molding window and, therefore, better associated moldability. The correlation of the moldability index and the ratio of R_{eq} to the plate thickness is shown in Figure 12. The moldability index increases with an increasing ratio of R_{eq} to the plate thickness for all plates 2, 2.5, and 3 mm thick. However, there exists no molding window when the ratio of R_{eq} to the plate thickness is lower than 1.5 for a semicircular gas channel plate. Generally, the ratio must be greater than approximately 2 for fair moldability to be obtained. This result is consistent with what is used in industry.

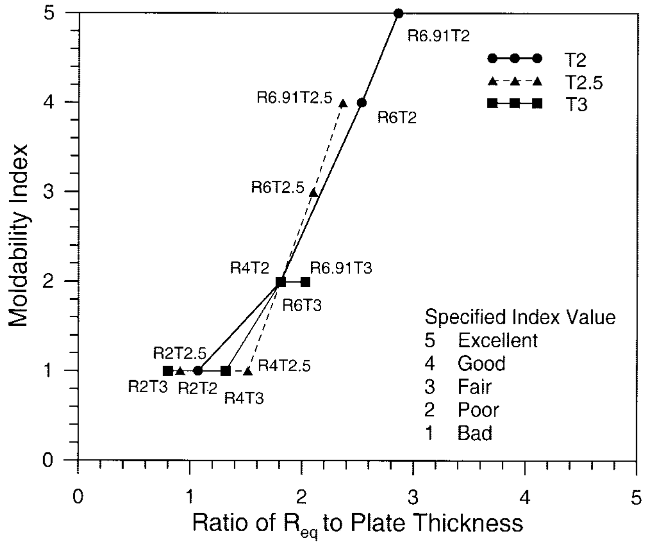


Figure 12 Variation of the moldability index versus the ratio of R_{eq} (for a semicircular gas channel) to the plate thickness.

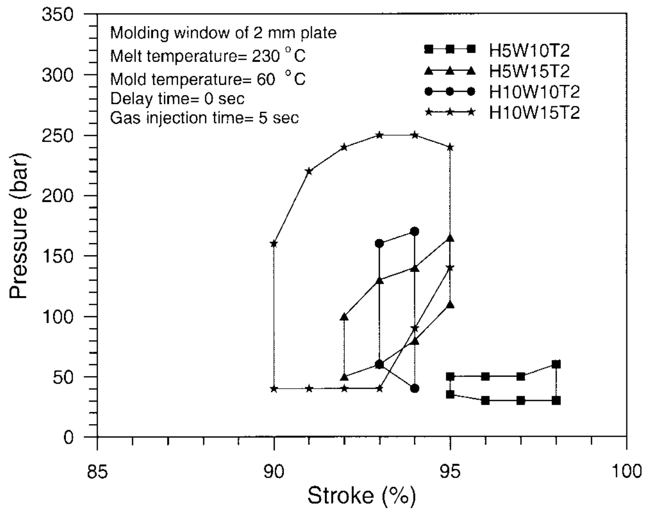


Figure 13 Molding windows for a 2-mm plate designed with rectangular gas channels of different sizes.

Moldability of parts with rectangular gas channel design

Graphic displays of molding windows with 2-, 2.5-, and 3-mm thick plates designed with rectangular gas channels of different width-to-height ratios can be found in Figures 13–15, respectively. The moldability index for different ratios of R_{eq} to the plate thickness is shown in Figure 16. Similarly to semicircular gas channels, for the rectangular gas channels, the area of the molding window increases with an increasing cross-section area. The effects of the width and height of a

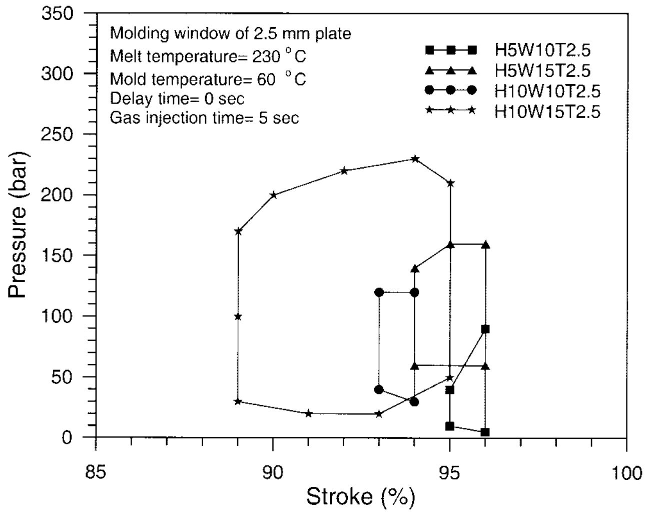


Figure 14 Molding windows for a 2.5-mm plate designed with rectangular gas channels of different sizes.

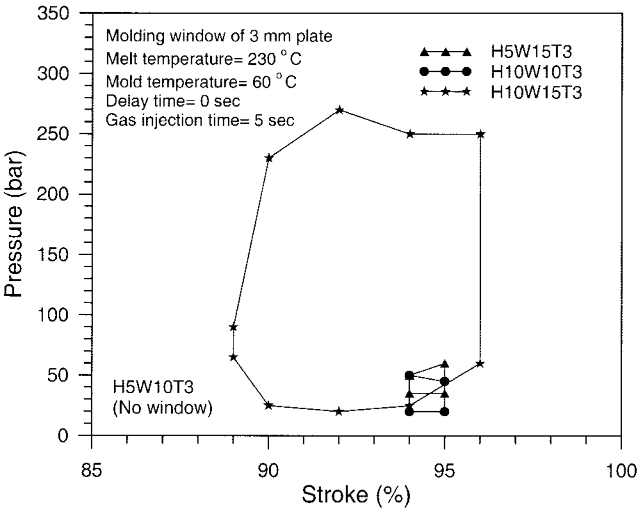


Figure 15 Molding windows for a 3-mm plate designed with rectangular gas channels of different sizes.

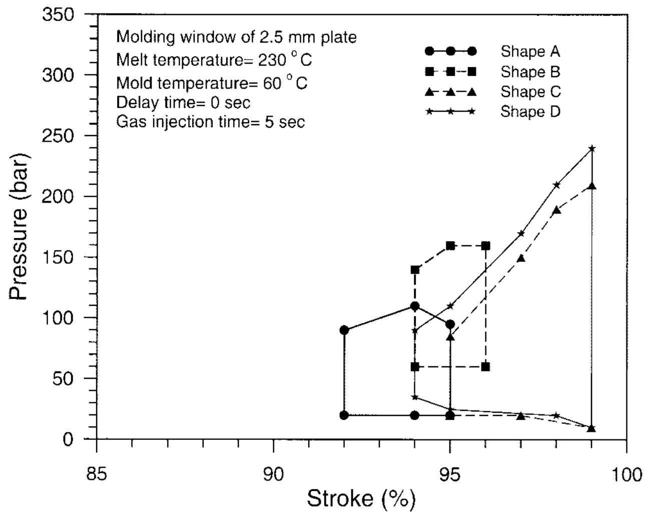


Figure 17 Molding windows for a 2.5-mm plate designed with four different gas channel designs.

rectangular gas channel on a molding window can also be analyzed with Figures 13–15. From these figures, the following observations have been made.

The molding window increases when the width of the gas channel is varied from 10 to 15 mm under the conditions of the same plate thickness and gas channel height. As the width of the rectangular gas channel increases, the moldability index also increases, and the enhancement effect is greater in 3-mm plate than in 2.5- and 2-mm plates. The results are consistent with the concept of relative flow resistance reduction. Alternatively, as for the influence of the height of the gas channel on the molding window, the molding window increases gradually when the gas channel is varied from 5 to 10 mm. Meanwhile, similarly to the width variation effect, as the height of the rectangular gas channel increases, the moldability index also increases, and the enhancement effect is greater in 3-mm plate than in 2.5- and 2-mm plates as well. The results are consistent with the relative flow resistance reduction.

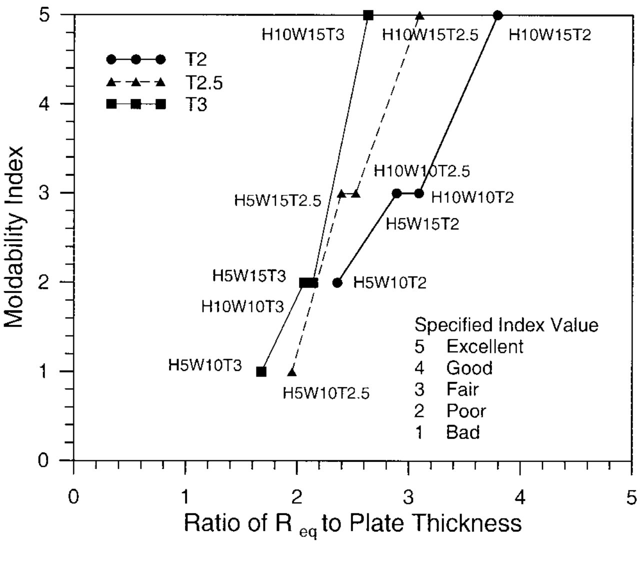


Figure 16 Variation of the moldability index versus the ratio of R_{eq} (for a rectangular gas channel) to the plate thickness.

From the results, it is evident that the height and width of the rectangular gas channel both play important roles in determining the associated molding window. Furthermore, under the condition of the same gas channel height (width), the moldability index increases with increasing gas channel width (height). For the same reason, for the gas channel with a semicircular cross section with a part thickness of 3 mm, the moldability index is also reduced because of the easy gas penetration into thin wall. However, the molding window will increasing dramatically when the cross section dimensions of the gas channel is enlarged (H10W15). Alternatively, as shown in Figure 16, the moldability index also increases with an increasing ratio of R_{eq} to the plate thickness. Basically, there is no molding window when the ratio of R_{eq} to the plate thickness is lower than 1.5. Similarly to the case of semicircular gas channels, the ratio must be greater than approximately 2 for fair moldability to be obtained.

Moldability of parts with four different gas channel designs

Figure 17 shows the molding window for 2.5-mm plates designed with four different types of gas channels. It is quite clear that the molding window shows a strong dependence on the gas channel shape. That shapes C and D can be molded under high pressures does not result in permeation. Therefore, gas channel designs attached to the top rib (shapes C and D) show greater advantages than designs of semicircular (shape A) and rectangular (shape B) gas channels. Meanwhile, in a comparison of the molding windows for semicircular and rectangular gas channels, the former show a slightly larger molding window area than the latter. This situation also occurred for H5W15T2 and R6.91T2 and H5W15T3 and R6.91T3 under the condition of same gas channel area. Thus, it is worthwhile to mention that the areas of the molding windows are in the order of D > C > A > B.

CONCLUSIONS

In this study, the effects of geometrical factors introduced by the part thickness and various gas channel geometries (including semicircular gas channels of different radii, rectangular gas channels of various width-to-height ratios, and four different types of gas channels) on molding windows were investigated. The molding window is defined in terms of a plot of the gas pressure versus the injection stroke for gas-assisted-injection-molded parts. The molding criteria that the gas penetration length must be over 80% along the gas channel and that gas permeation must be within 1 mm on both sides of the gas channel were chosen for determining the molding window. On the basis of the measured results, the following conclusions can be made:

1. With the same gas channel section area, both gas channel designs attached to the top rib (shapes C and D) provide better moldability than the other two gas channel designs (shapes A and B) for 2.5-mm-thick plates.
2. With the same channel section area, the gas channel designed with a semicircular cross section (R6.91) provides better moldability than that of a rectangular cross section (H5W15) for 2-, 2.5-, and 3-mm-thick plates.
3. The moldability index increases with an increasing ratio of the gas channel R_{eq} value to the part thickness for both semicircular and rectangular gas channel designs. Generally, for an appropriate molding window to be obtained, the ratio should be greater than 2.
4. For GAIM parts with rectangular gas channels, under the condition of the same gas channel height (width), the molding window increases with increasing gas channel width (height).

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