Study on the Residual Wall Thickness at Dimensional Transitions and Curved Sections in Gas-Assisted Molded Circular Tubes

S. Y. YANG* *and* H. L. CHOU

Grace Laboratory for Polymer Processing
Department of Mechanical Engineering
National Taiwan University
Taipei 106, Taiwan, R.O.C.

Plastic tubes and hollow rods can be fabricated using gas-assisted injection molding technology with reduced cost. The residual wall thickness around dimensional transitions and curved sections is of great concern. This research investigated the uniformity of the residual wall thickness distribution in circular tubes with dimensional variations and curved sections. It was found that the wall thickness was not uniform near transitions. With the addition of fillets with proper angles around transitions, the uniformity of residual wall could be greatly improved. The residual wall thickness in curved sections was thick around the outer wall and thin around the inner wall. Low melt temperature and high gas pressure were found to reduce the deviation in the wall thickness around curved sections.

INTRODUCTION

Gas-assisted injection molding (GAIM) has emerged as one of the most innovative technologies in the injection molding industry. Many applications have been found and many more have been evaluated for automotive components, consumer products and business machines. Two basic types of parts can greatly benefit from gas-assisted molding: large flat parts with ribs (such as large TV housings and automotive panels) and components with thick sections (such as shower handles and hollow handsets). Many researchers have investigated issues related to ribbed large plates (for example, 1–9). On the other hand, gas-assisted injection molding of thick parts has rarely been studied. Poslinski *et al.* (10) studied gas-assisted displacement of viscoplastic liquids in tubes. Chen *et al.* (11) investigated gas penetrating characteristics in a spiral tube. But several key problems have not been systematically investigated. For instance, most hollow tubes are not uniform in dimensions throughout the length of the tube. The residual wall thickness around dimensional transitions is a critical factor determining the quality of such tubes. Another common feature of tubes is the presence of curved sections. The wall thickness is not uniform in gas-assisted molded curved tubes (12). The mechanism involved and its relation to processing conditions about this non-uniformity have not been fully investigated. To enhance the technology of gas-assisted molding of tube-shaped parts, systematic study of the residual wall thickness near dimensional transitions and curved sections is greatly needed. This paper is devoted to investigating: 1) the distribution of the residual wall thickness in gas-assisted molded tubes with contractional and expansional transitions; 2) the mechanism of this distribution of the wall thickness; 3) the effects of adding fillets to transitions on improvement of the uniformity of the residual wall thickness; and 4) the distribution of the residual wall thickness in curved sections and its relation to processing conditions.

EXPERIMENTAL SETUP

Gas-assisted injection molding experiments were conducted with a 50-ton injection molding machine (Polypax, GG50, Taiwan). A lab-produced gas injection unit was attached to the machine. The gas-injection system consisted of a nitrogen tank, pressure regulators, valves, a solenoid, and a controller for gas-injection delay control (4).

The typical geometry of the cavities in the molds constructed for this experiment is shown in *Fig. 1*. The part essentially consists of sections of diameter A, diameter B and again diameter A. Two types of molds,

*To whom correspondence should be addressed.

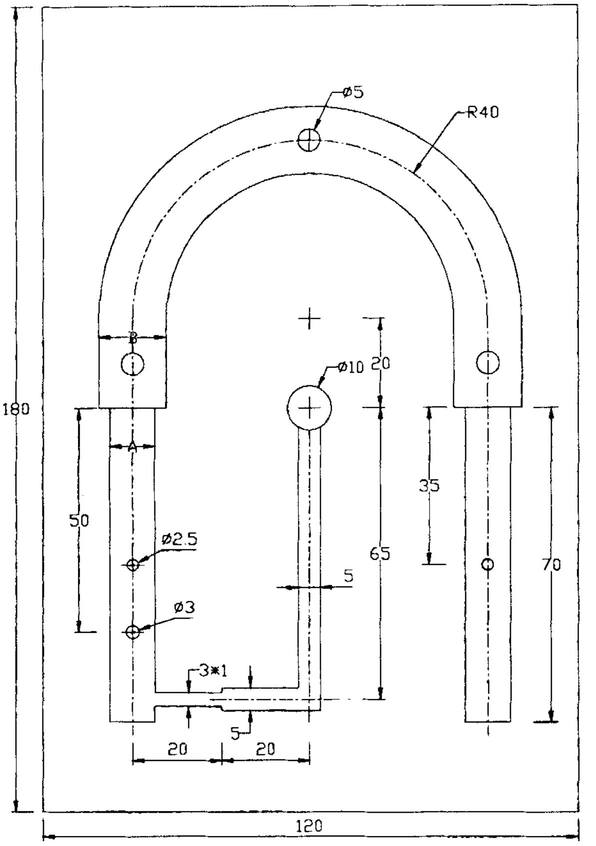


Fig. 1. Sketch of the mold geometry showing the cavity unit: mm, for gas-assisted molding of circular tubes with dimensional transitions and curved sections.

namely EC and CE (EC implies expansion followed by contraction), were constructed. Six sets of molds for cavities with different dimensional changes along with the mold REF without any transitions are shown in *Table 1*. The cavity in mold EC1 consisted of 5D-10D-5D sections, while that in mold EC2 consisted of 10D-15D-10D sections. The cavity in mold CE1 consisted of 15D-7.5D-15D sections, while that in mold CE2 consisted of 15D-10D-15D sections. To investigate the effects of adding transitional fillets on the wall thickness distribution, fillets of 45° were added to the transitions in mold EC1 (to construct mold EC1A), and fillets of 30° were added to the transitions in mold CE1 (to construct CE1B) as shown in *Fig. 2*. The mold REF was also used to investigate the unsymmetrical residual wall distribution in curved sections.

After the tubes were gas-assisted injection molded, the sections near the transitions or curved sections were sliced along the longitudinal direction. To observe the distribution of the residual wall thickness, inks were applied to the sliced sections, and then the sections were stamped onto paper to reproduce the geometry of the residual wall. Thickness distributions around curved sections were measured at four locations of 45°, 90°, 112.5° and 135° as shown in *Fig. 3*.

An injection grade polypropylene PP-F1004EF (SHENG-JU, Taiwan) was used in this study. The underlined processing conditions given below were employed in a typical operation (the others were used to investigate the effects of the processing conditions):

melt temperature: 200°C, 220°C, 240°C;
mold temperature: 40°C, 50°C, 60°C, 70°C;
injection rate: 30%, 50%, 70%;
short-shot size: 85%, 90%, 95%;
gas pressure: 40bar, 60bar, 80bar;
gas delay time: 1.5s, 3.5s, 5.5s, 7.5s.

RESULTS AND DISCUSSION

■ Residual Wall Thickness at Expansional Transitions

a. Expansional Transitions Filled With Melt Before Gas Injection

The residual wall distribution at expansional transitions depends on whether that specific transition section is filled with melt at the instant of gas injection. *Figure 4* shows the residual wall distribution at expansional transitions which were filled with melt, before gas injection. These transitions were located upstream at the dimensional change from 10D to 15D (in mold EC2). Similar residual wall distribution was observed at expansional transition 5D to 10D filled with melt before gas injection (in upstream of mold EC1). Melt filled the transitions and cooled down, forming a frozen layer near the cavity wall, before gas injection. It is observed that residual melt accumulated around the corners after gas injection. The inner boundary of the residual wall did not resemble the geometry of the cavity wall. Rather, a 45° edge appeared, indicating that the length of the residual wall after gas injection

Table 1. Circular Tube Cavities Used in This Study.

Mold Notation	Diameter A (mm)	Diameter B (mm)	Diameter A (mm)	Fillet
EC1	5	10	5	None
EC2	10	15	10	None
CE1	15	7.5	15	None
CE2	15	10	15	None
EC1A	5	10	5	45°
CE1B	15	7.5	15	30°
REF	10	10	10	None

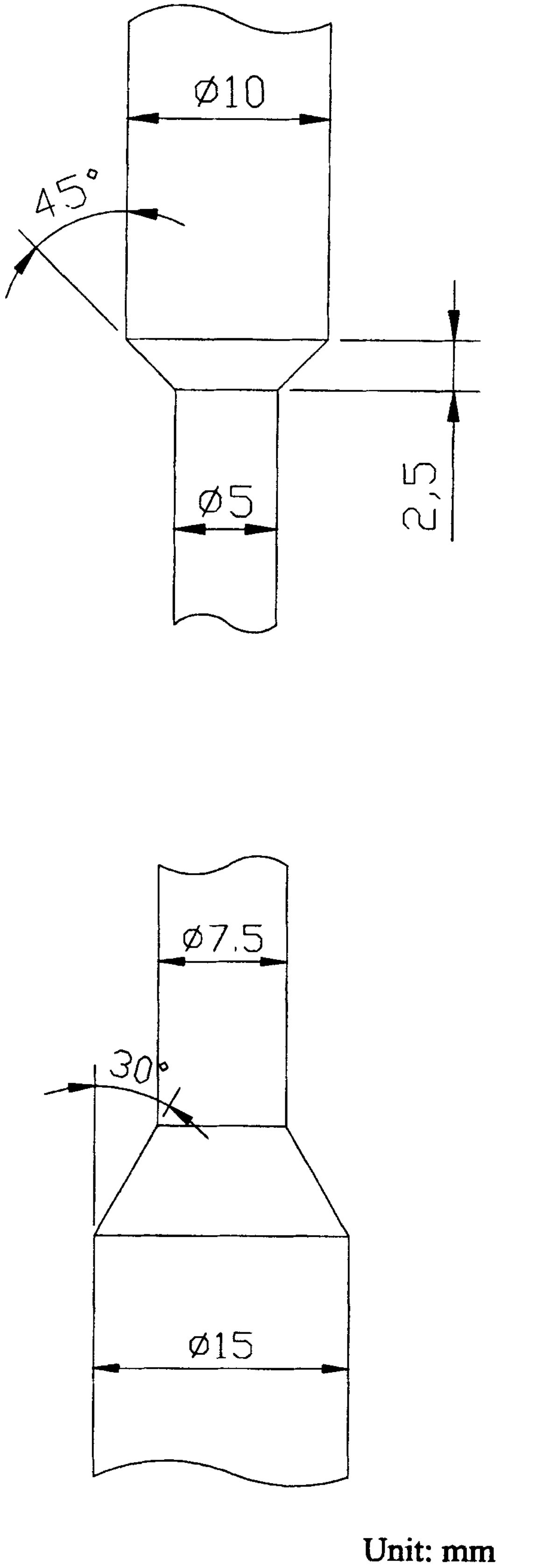


Fig. 2. Fillets of 45° (EC1A) and 30° (CE1B) added to smooth the transitions.

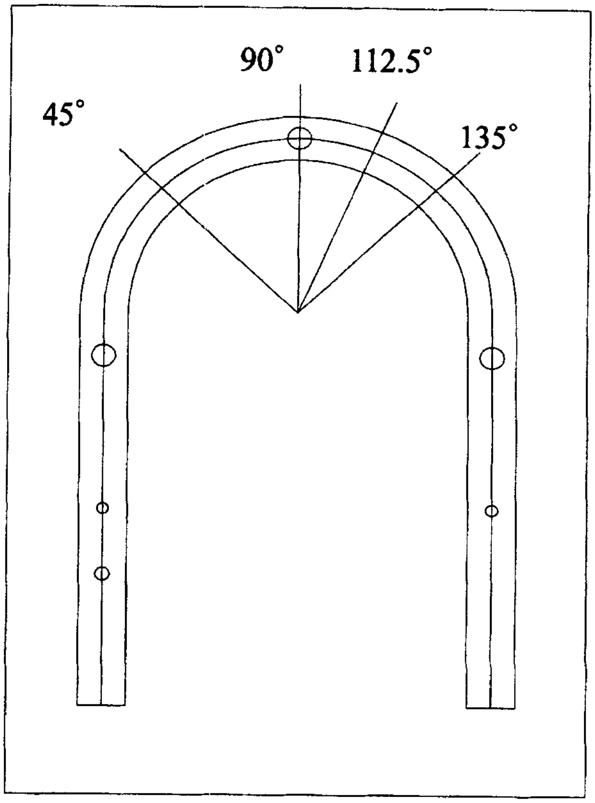


Fig. 3. Schematic drawing showing the measurement sections for study of the residual wall thickness at curved sections.

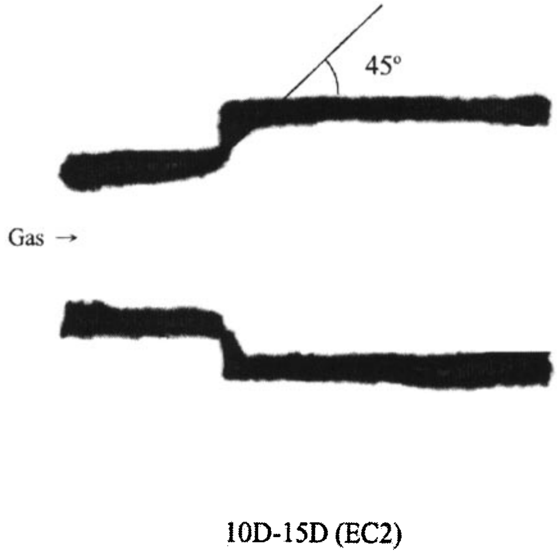


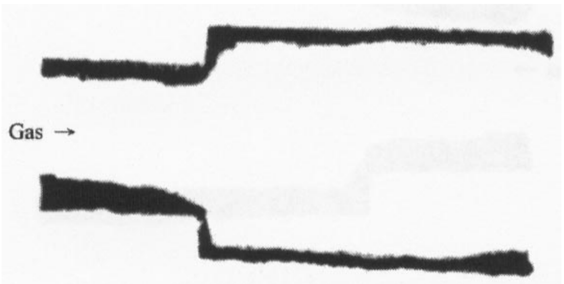
Fig. 4. Residual wall distribution at expansional transitions filled with melt upon gas injection (upstream of molds EC2). The melt in the corners has accumulated, leaving an approximately 45° edge.

approximately equaled the depth of expansion, which was half of the diameter difference. The above can be explained as follows: When gas flows through a sharp transition from a small tube to a suddenly expanded tube, there is always a reattachment point located at a certain distance downstream. This distance can be denoted as x times the expansion depth h, where x is a fixed ratio. A circulation flow is always observed in the corner. But when the corner is pre-filled with solidifying melt, the gas pressure at the reattachment point is not high enough to expel viscous melt or to establish circulation flow. The melt remains in the corner, leaving the residual wall resembling the streamlines.

b. Expansional Transitions
Not Filled With Melt Before Gas Injection

Figure 5 shows the residual wall thickness at expansional transitions that were not filled with melt until gas-assisted filling occurred. These transitions appear downstream at the dimension change from 10D to 15D (in mold CE2). Similar residual wall distribution was observed at expansional transition 7.5D to 15D not filled with melt until gas injection (in downstream of mold CE1). There was little melt accumulation in the corners. The residual wall thickness was uniform, and the boundary of the residual wall resembled the tube geometry. This can also be explained based on fluid dynamics.

After gas is injected in, the gas drives melt through the empty expansional transition to fill the tube cavity. The speed of gas penetration is high. In fact, the velocity of the gas tip rises exponentially with time (13). At downstream locations, melt driven by gas flows through abrupt expansional transitions; after a reattachment point, circulation flow is established around the corner, preventing the accumulation of melt in the corner. The residual wall in such expansional transitions, which are not filled with melt, is just a thin layer of melt coating the cavity wall.



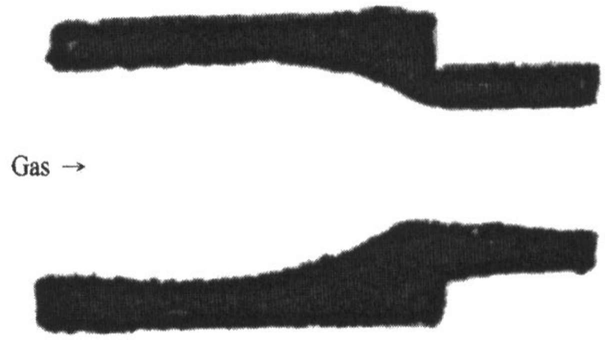
10D-15D (CE2)

Fig. 5. Residual wall distribution at expansional transitions not filled with melt upon gas injection (downstream of molds CE2). The residual wall is a thin layer of melt, which coats the cavity wall during gas-assisted filling.

Residual Wall Thickness at Contractional Transitions

Figure 6 shows the residual wall distribution at contractional transitions filled with melt during conventional filling. These transitions were located upstream at the dimensional change from 15D to 10D (in mold CE2). Similar residual wall distribution was observed at contractional transition 15D to 7.5D filled with melt before gas injection (in upstream of mold CE1). The boundary of the residual wall did not resemble the geometry of tube. A smoothly convergent boundary appeared. The geometrical obstacle due to contraction caused the gas to change in flow direction and resulted in convergent streamlines. The smooth accumulation of melt near contractions resembled the streamlines.

Figure 7 shows the residual wall thickness at contractions that were not filled until gas-assisted filling occurred. They appeared downstream at the dimensional change from 15D to 10D (in mold EC2). Similar residual wall distribution was observed at contractional transition 10D to 5D not filled with melt until gas injection (in downstream of mold EC1). A smoothly convergent boundary was also observed; geometrical obstacles due to contraction caused accumulation of melt near contractions, leaving the boundary of the residual wall resembling the streamlines. It can be concluded that the boundary of the residual wall in a contractional transition always resembles the streamlines of gas flowing through the contraction, no matter whether it is filled with melt or not when gas injection occurs. The geometrical obstacle is the dominant factor influencing a contractional transition.

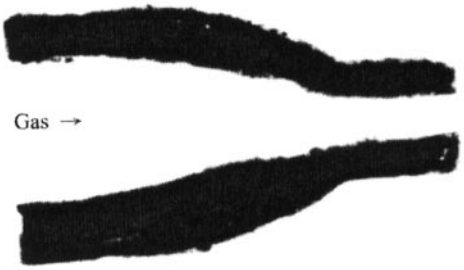


15D-10D (CE2)

Fig. 6. Residual wall distribution at contractional transitions filled with melt upon gas injection (upstream of molds CE2). Geometrical obstacles due to contraction cause melt accumulation at contractional transitions filled with melt upon gas injection, resulting in a boundary of the residual layer resembling streamlines.

15D-10D (EC2)

Fig. 7. Residual wall distribution at contractional transitions not filled with melt upon gas injection (downstream of molds EC2). Geometrical obstacles due to contraction cause melt accumulation, resulting in a boundary of the residual layer resembling streamlines.



15D-7.5D with 30° fillet (CE1B)

Fig. 9. Residual wall thickness at contractional transitions with 30° fillets filled with melt before gas injection. The uniformity of the wall thickness in the transitions is improved, but the improvement is not as obvious as in Fig. 8. The fillet angle should resemble the original residual wall boundary for best uniformity.

Residual Wall Thickness in Transitions With Fillets

Figure 8 shows the residual wall thickness at expansional transitions with 45° fillets filled with melt before gas injection. The figure shows tubes that were gas-assisted molded with mold EC1A. The uniformity of the wall thickness in the transition region is seen to be greatly improved due to the addition of a 45° fillet. The fillet angle is found to be close to that of the original residual wall boundary. When the fillet shape resembles the original boundary of the residual wall, the best wall uniformity can be expected. *Figure 9* shows the residual wall thickness at initially filled contractions with 30° fillets. The figure shows tubes that were gas-assisted molded with mold CE1B. The uniformity of wall thickness in the transition region is seen to be improved. However, the effect is not as obvious as with the addition of 45° fillets in terms of expansion. The shape of the fillet should resemble the inner boundary of the original residual wall at the transition without a fillet for best uniformity.

5D-10D with 45° fillet (EC1A)

Fig. 8. Residual wall thickness at expansional transitions with 45° fillets filled with melt before gas injection. The uniformity of the wall thickness in the transtions is greatly improved.

Residual Wall Thickness in Curved Sections

Figure 10 shows the wall thickness difference in curved sections that were gas-assisted injection molded at different melt temperatures (with the same mold temperature). The percentage difference of the wall thickness is defined as:

Difference = (outer wall thickness − inner wall thickness) / average thickness.

In all cases, the inner wall was thinner than the outer wall. When gas penetrated the melt, it sought the path of least resistance. In curved sections, the pressure differences between the gas tips and melt fronts at all radii were the same (which was the gas pressure). But the distances at different radii were different; the distances between the gas tips and melt fronts increased with the increase of the radius. The driving force for gas penetration (which is proportional to the pressure difference divided by the distance) thus decreased with the increases of the radius. As a result, the residual wall thickness around gas-assisted molded curved sections was not axial-symmetrical. Rather, the residual wall thickness of the outer wall was greater than that of the inner wall.

a. Effect of Melt Temperature

Figure 10 also shows that the wall thickness difference increased when the melt temperature increased. Higher melt temperatures caused the melt viscosity and the flow resistance to decrease. With low flow resistance, the difference in the driving force (which was higher near the inner wall) resulted in a larger wall thickness difference.

Figure 10 shows in detail the wall thickness difference in four sections and along the curved sections as well. The difference in the thickness of the outer and inner walls did not remain constant from upstream to downstream locations. With low melt temperatures, the maximum wall thickness difference occurred at 90 degrees. Above 90 degrees, the centrifugal force effect caused the wall thickness difference to decrease. At a high melt temperature (240°C), the effect of centrifugal force was even more significant. The maximum wall difference occurred at 45 degrees, and the wall thickness difference decreased as the angle increased.

b. Effect of Mold Temperature

Figure 11 shows the measured wall thickness difference in curved tubes molded under the same melt temperature, but with different mold temperatures. The effect of the mold temperature was different from that of the melt temperature because only the local melt temperature near the wall was affected by the mold temperature. Increasing the mold temperature caused the wall thickness difference to decrease and moved the maximum difference to an upstream curved section. Since the melt temperature was the same, the melt in the core remained essentially at the same temperature even though the mold temperatures were different. However, a high mold temperature caused the thickness of frozen layer to decrease. Centrifugal force was exerted on more of the melt and had a significant effect.

c. Effect of Gas Pressure

Figure 12 shows the measured wall thickness difference in four sections of the curved sections with varying gas pressure. The wall thickness difference decreased as the gas injection pressure increased. An increase of the gas injection pressure caused the kinetic energy of the gas to increase during gas-assisted filling phase. Higher gas kinetic energy led to higher centrifugal force and caused the wall thickness difference to decrease in the curved sections.

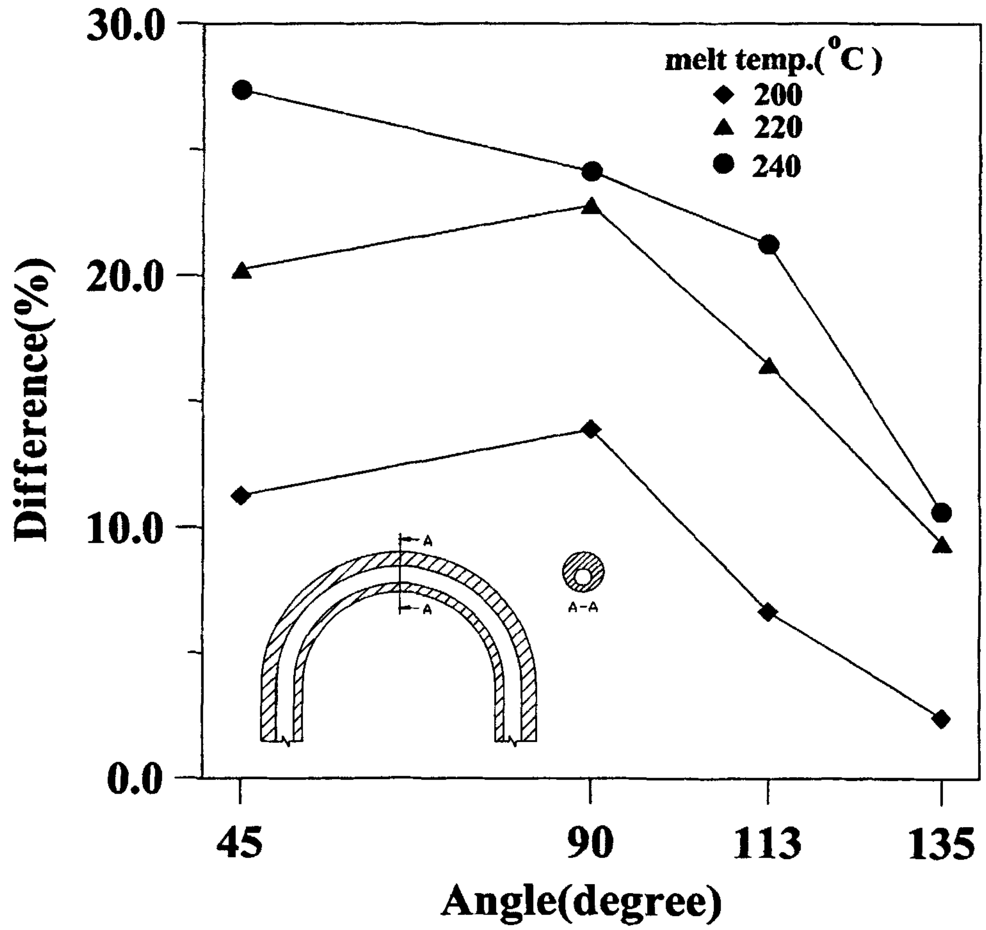


Fig. 10. Wall thickness distribution measured at four locations along curved sections. The wall thickness difference increases as the melt temperature increases. The difference in the thickness of the outer and inner walls is not constant along the curved section. The centrifugal force effect influences the difference in wall thickness. A high melt temperature shifts the maximum difference upstream.

d. Effect of the Gas Delay Time

Figure 13 shows that the wall thickness difference decreased as the gas delay time increased. An increase of the gas delay time csaused the cooling time of the polymer melt to increase. Therefore, the increase of the gas delay time parameter was correlated with a decrease of the melt temperature. A short gas delay time resulted in a high melt temperature, which caused the melt viscosity and flow resistance to decrease. With low flow resistance, the difference in the driving force (which was higher near the inner wall) resulted in a large wall thickness difference.

SUMMARY AND CONCLUSIONS

The residual wall distribution in gas-assisted injection molded tubes with sudden dimensional transitions and curved sections was investigated in this work. Based on this the findings of this study, the following conclusions can be drawn:

1. The distributions of the residual wall thickness near an expansional transition depended on the melt filling conditions at that specific transition. If the transition was filled with melt before gas injection, significant melt accumulated near the expansional corner, forming a 45° boundary. On the other hand, if the transition was not filled until gas blow-in proceeded, no accumulation of melt was found in the corner. Only a thin uniform layer of melt remained as the residual wall. The flow of gas at a sudden expansion always created a reattachment point downstream. The pressure at the reattachment point was large enough to create a circulation flow if the transition was not filled until gas blow-in proceeded. But the pressure was not sufficient to create a circulation flow if the transition was originally filled with melt.
2. Adding fillets at transitions improved the uniformity of the residual wall thickness near the transitions. For transitions that were melt-filled before gas injection, a 45° fillet angle was found to be proper for expansional transitions. Addition of a 30° fillet led to improved uniformity of the wall thickness near a con-

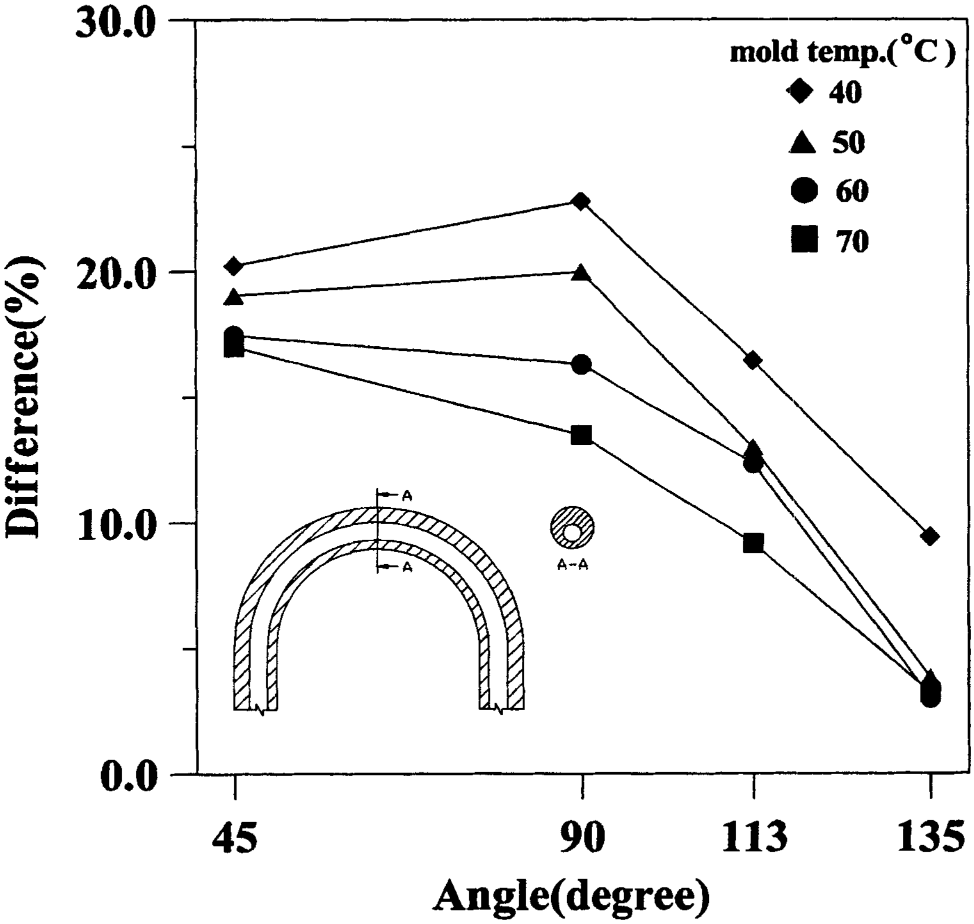


Fig. 11. Measured difference in the wall thickness of curved tubes molded with at the same melt temperature, but with different mold temperatures. Increasing the mold temperature causes the difference in wall thickness to decrease and moves the maximum difference upstream.

tractional transition, but it was not optimal. The optimal fillet angle resembled the boundary of residual wall, which was determined mainly by the temperature distribution and gas flow conditions.

3. The wall thickness in curved sections was not axial-symmetrical. Because the distance between the gas tip and melt front was shorter near the inner wall, more gas penetrated near the inner wall. The residual inner wall was thus always thinner than the outer wall. The difference in thickness between the outer and inner wall decreased at a low melt temperature, at a high mold temperature and under a long gas delay time. The effect of the melt temperature was most significant.
4. For a tube with a circular section of 180 degrees, the wall thickness difference did not remain the same throughout the section at different angles. The maximum wall thickness difference generally occurred upstream. It may have been shifted upstream because of the centrifugal force. The centrifugal force effect tended to diminish the effect of the pressure gradient difference due to the variation of the radius. This centrifugal force effect was most obviously demonstrated by the gas pressure and gas delay time.

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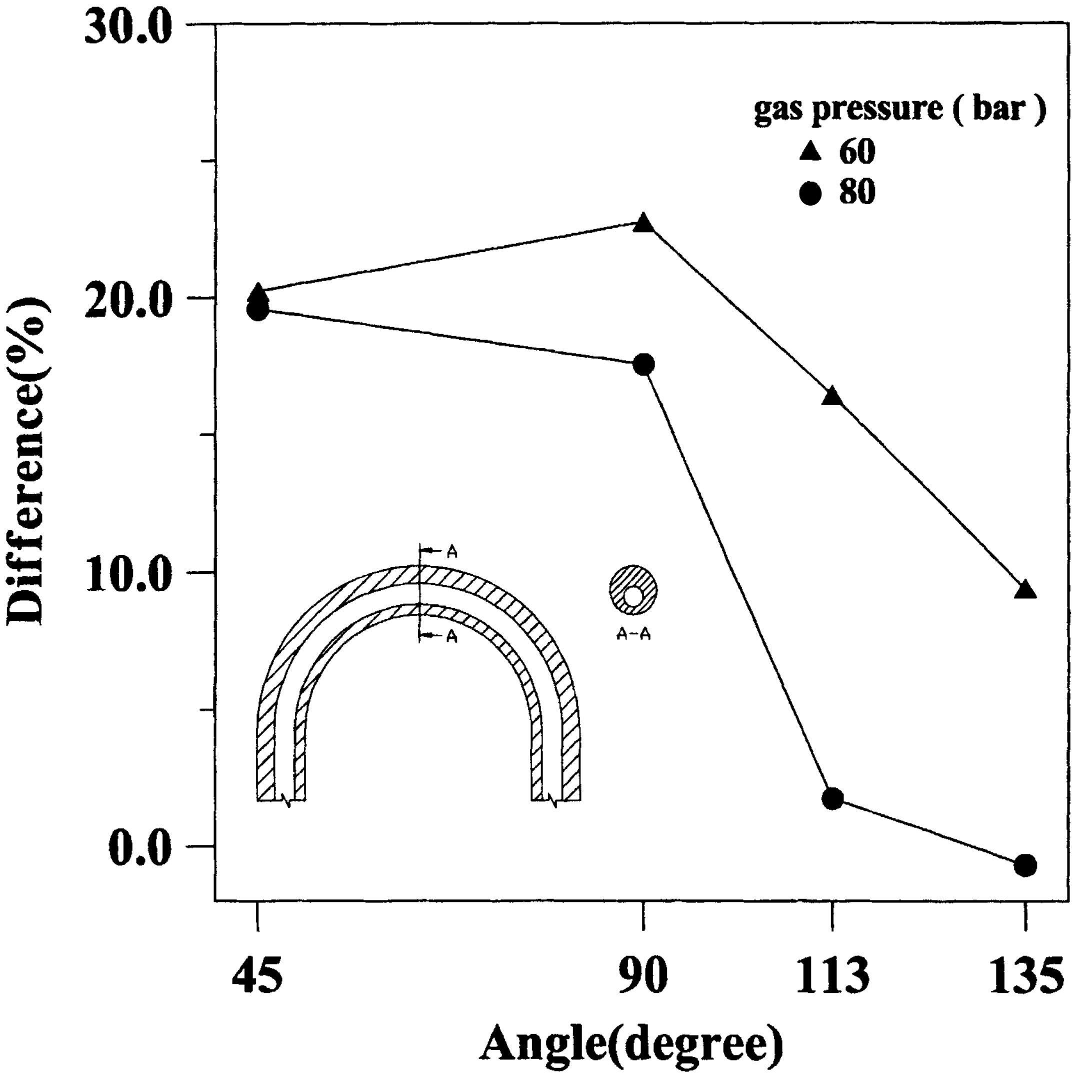

Fig. 12. Effect of gas pressure on the difference in wall thickness of molded curved tubes. Increasing the gas pressure causes the difference in wall thickness to decrease.

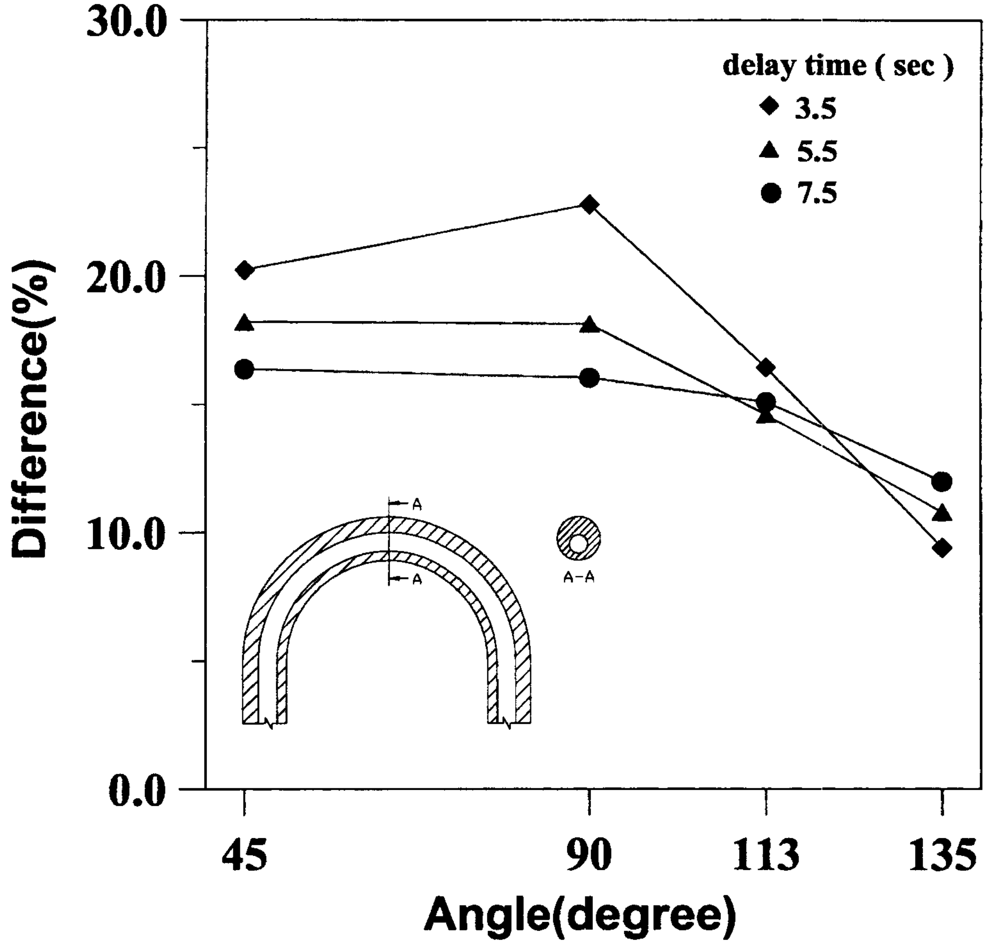

Fig. 13. Effect of the gas delay time on the difference in wall thickness of molded curved tubes. Prolonged gas delay causes the cooling time to increase and the melt temperature to decrease. A long gas delay time causes the difference in the wall thickness to decrease. The centrifugal force effect is greatly diminished by prolonged gas delay.

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