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Effect of processing parameters on water penetration in water assisted injection molding of ABS

Summary — This study experimentally investigates the effect of processing parameters on water penetration and part hollow-core characteristics (includes wall thickness, core diameter) and shrinkage of the plastic molded part, in Water Assisted Injection Molding process (WAIM) of an amorphous polymer. WAIM has been developed for production of hollow plastic parts and is suitable for weight reduction of large parts with a good internal surface. Other benefits are fast cooling and short cycle time without compromising part quality. In this study acrylonitrile-butadiene-styrene (ABS) was chosen as the candidate amorphous polymer. The selected processing parameters were: water injection delay time, holding time and mold temperature. The mold cavity shaped a branched pipe (two-head) to be cored out *via* water penetration. Actual factory-like experiments and full shot size were applied during this research. The results showed that the longest water penetration, the least wall thickness differential, the highest uniformity in pipe diameter and the lowest shrinkage are obtained when the process parameters such as holding time and mold temperature are maintained at the highest level and delay time is optimized.
Keywords: water assisted injection molding, WAIM, water penetration, hollow part, ABS.

WPŁYW WARUNKÓW PRZETWARZANIA NA PENETRACJĘ WODY PODCZAS FORMOWANIA ABS W PROCESIE WTRYSKIWANIA WSPOMAGANEGO WODĄ

Streszczenie — Omówiono zależność penetracji wody w uplastycznionym, znajdującym się w gnieździe formy tworzywie ABS (akrylonitryl-butadien-styren) oraz charakterystyki wytwarzanych elementów (grubości ścianki, średnicy kanału, skurczu) od parametrów procesu wtryskiwania wspomaganego wodą (WAIM), takich jak: opóźnienie wtrysku wody (*delay time*), czas docisku (*holding time*) oraz temperatura formowania. Badania prowadzono podczas formowania rozgałęzionej, dwuramiennej rurki, której pusty rdzeń uzyskiwano dzięki penetracji wtryskiwanej wody (tabela 1). Wyniki wskazują, że kształtki o najlepszej charakterystyce, tj. odpowiedniej długości penetracji wody w ciekłym ABS, małej różnicy grubości ścianek, jednakowej średnicy pustego rdzenia i małym skurczy można otrzymać stosując długi czas docisku (10 sec), wyższą temperaturę formowania (50 °C) i niedługi czas opóźnienia wtryskiwania wody (2,5 sec) (rys. 1—9).
Słowa kluczowe: wtryskiwanie wspomagane wodą, WAIM, penetracja wody, elementy puste, opóźnienie wtrysku wody, czas docisku, temperatura formowania.

WAIM (Water Assisted Injection Molding) is one of the plastic manufacturing technologies which is able to produce both thick and thin parts with less shrinkage, warpage and sink mark. In the recent years, the WAIM technology has received extensive attention. This process has been developed at the Institute of Plastic Processing (IKV), Aachen, Germany [1].

WAIM has some advantages over GAIM process (Gas Assisted Injection Molding). This is because water is incompressible, inexpensive, readily available, and a more effective coolant. In this process, injected molten material is cooled from inside and thus, cooling time is lowered up to 50 to 70 % compared to that of GAIM process. The advantages also include: saving material, ability to produce complex parts consisting of both thick and thin sections, less shrinkage and warpage and especially better surface quality without compromising part properties. WAIM has become a significant technology in plastic processing industry and a subject of research interest [2]. Below is the updated (compared to an earlier version published in [3]) review of research on water penetration assisted injection molding.

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Liu *et al*. [4] performed an experimental study on WAIM of glass fiber filled poly-butylene-terephthalate (PBT) composites. A plate cavity with a rib crossing the center was used in the experiments. The influence of various processing variables on the length of water penetration in molded parts was examined. They found out that the melt filling pressure, melt temperature, and short shot size were the dominant parameters affecting the water penetration behavior. A higher degree of crystallinity was exhibited at the mold-side than that at the water-side. They reported that glass fiber filled composites exhibit more severe water fingerings than those of un-filled materials.

Liu and Wu [5] studied the dynamic visualization of cavity-filling process in fluid-assisted injection molding. They reported the filling phenomena of fluid-assisted injection moldings by using a dynamic visualization technique in semi-crystalline polypropylene material. They showed that water-assisted injection molded polypropylene plates exhibit a more uniform hollowed core ratio inside the plates than those molded by gas-assisted injection molding. During post-filling of water-assisted injection molding, the solidifying polymer undergoes volumetric shrinkage, allowing water to penetrate into the parts.

Liu and Huang [6] studied the fountain flow in water-assisted melt filling. They built a newly-developed water injection system and emulated mold to investigate the melt flow patterns during water-assisted melt filling. The experimental results showed the forming of fountain flow in water-assisted melt filling and revealed the formation of fountain flow during melt filling under application of high pressure of water.

Lin and Liu [7] investigated the fingering phenomenon in fluid-assisted injection-molded disk parts. The used a reciprocating injection-molding machine equipped with gas- and water-injection units. They used polypropylene (PP) as the polymeric material and a disk cavity with two different thickness levels was used for all experiments. They found out that the fluid assisted filling process is an unstable system by nature. Any small perturbation by materials viscosity or by temperature gradient can trigger the unbalance of gas (water) penetrations in the parts and result in fingerings. The experimental results suggested that water-assisted injection molded parts exhibited more severe fingerings than gas molded parts. Furthermore, the experimental results suggested that the melt short shot size and mold temperature were the principal parameters affecting the formation of part fingerings.

Bociaga [8], while giving a review of the water/gas assisted molding process, presents the possibility to use these techniques in the production of various goods, applied in many industries.

The current paper presents an extensive experimental work on the effect of processing parameters on the penetration behavior of water in the WAIM process of ABS as a amorphous polymer. The authors already published data on WAIM process of the semi-crystalline polymer (PP) [3] and continued work to observe the behavior of an amorphous polymer. The desired element was a branched (two-head) pipe for which a conventional tooling could not be devised for injection molding. The purpose was to observe the effect of delay time, holding time and mold temperature on water penetration length, hollow core diameter, wall thickness deference, and shrinkage at both pipe heads.

EXPERIMENTAL

Materials

— Acrylonitrile-butadiene-styrene (ABS), grade 750 SW, KUMHO an amorphous thermoplastics, was used in the experiments.

Molding process

A laboratory injection molding machine (clamping tonnage of 70) was utilized to produce parts. A mold was designed for the branched pipe and manufactured to include an over-flow channel (see Fig. 1 in [3]). This was to secure the complete filling of the cavity before water injection. Thus, the injected water pushes the melt into the over flow channel to core-out the part.

Appropriate nozzle for water-injection was designed in order to present a consistent and un-interrupted molding process. The nozzle was located at a distance of 10 mm from the gate.

A control unit was implemented containing a high pressure cylinder as a water reservoir, a high pressure N_2 cylinder to pressurize and pump the water, a regulator to set the required water pressure and the timers in order to adjust injection delay time and holding time at the desired levels (see Fig. 2 in [3]).

Three selected processing parameters were delay time, holding time and mold temperature. Four levels of delay times were chosen as: 0, 2.5, 5 and 10 sec. Two levels of holding times were chosen as 5 and 10 sec. Mold temperature was set at three levels: 30, 40 and 50 °C. The total number of data points was then 24 (Table 1). To obtain reliable data, at least three experiments were carried out for each data point after a steady process was reached.

The injection shot size was first adjusted to completely fill the mold cavity. A slight overflow was permitted to ensure complete cavity filling. The shot adjustment was then kept intact in all experiments. A micro-switch was then activated at the end mold of filling to transmit a signal to a timer, allocated for delay time set at the desired value (while terminating the melt injection). After elapsing the delay time, a signal was then transmitted to the high-pressure solenoid valve to allow pressurized water to be injected into the mold and to penetrate the melt to core-out the part. The holding pressure was then maintained for a determined time adjusted by the corresponding timer. When the holding time lapsed, the pressure was released.

T a b l e 1. Processing conditions selected for the experiments

Experiment No	Delay time, sec	Holding time, sec	Mold temp., °C
1	0	5	30
2	2.5	5	30
3	5	5	30
4	10	5	30
5	0	10	30
6	2.5	10	30
7	5	10	30
8	10	10	30
9	0	5	40
10	2.5	5	40
11	5	5	40
12	10	5	40
13	0	10	40
14	2.5	10	40
15	5	10	40
16	10	10	40
17	0	5	50
18	2.5	5	50
19	5	5	50
20	10	5	50
21	0	10	50
22	2.5	10	50
23	5	10	50
24	10	10	50

The mold temperature was measured with thermocouples placed at 10 mm depth into the mold wall. The melt temperature was maintained and frequently checked with laser perimeter before injection. The melt temperature was fixed and found out to be 230 °C in all experiments.

The molded parts were sectioned and designated along their lengths. The selected sections starts at 50 mm distance from the gate and ends along the straight leg at the length of 140 mm (L_1) and along the curved leg at the length of 153 mm (L_2) ([3], Fig. 3).

The diameters of the hollowed cores and the maximum and minimum wall thicknesses (thickness difference) were then measured at each section (and for both heads) as shows in [3] in Fig. 4.

RESULTS AND DISCUSSION

The effects of processing variables (delay time, holding time, and mold temperature) on water penetration, wall thickness, inner diameter, and shrinkage are presented in Figures 1—9.

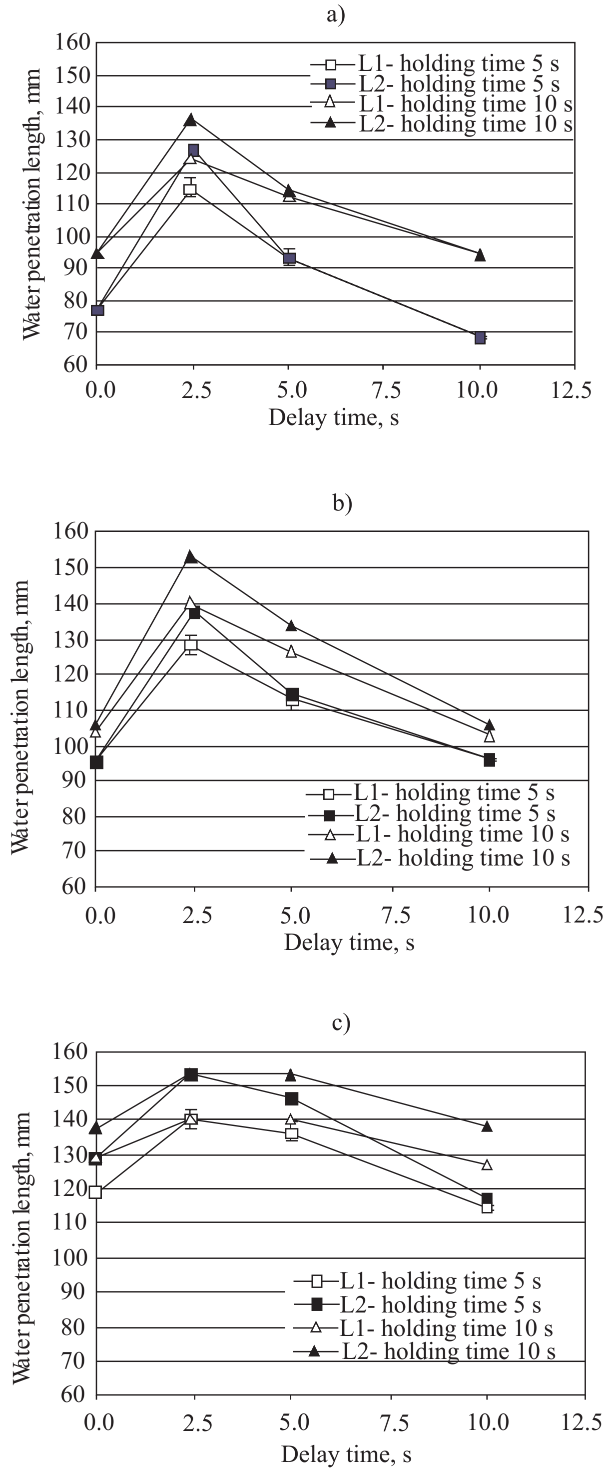


Fig. 1. Effects of delay time and holding time on water penetration length in the straight (L_1) and curved leg (L_2) of element at various mold temperatures: a) 30 °C, b) 40 °C, c) 50 °C

Figure (1a—c) shows the effect of delay time on water penetration at various mold temperatures and holding times. The figure shows that, regardless of the mold temperature and holding time, the water penetration increases with increasing delay time to a maximum level and then decreases. The maximum water penetration

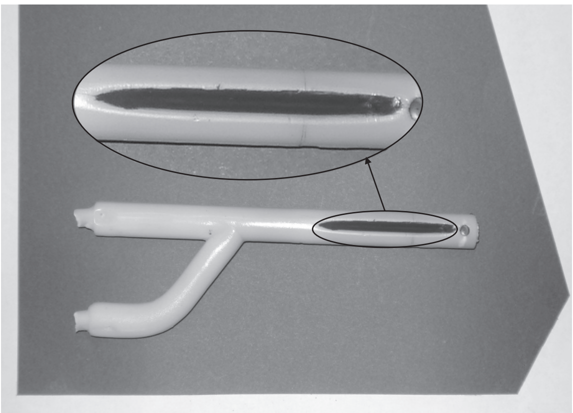


Fig. 2. Sample produced at a delay time of 0 sec showing a long sink mark close to the gate, marked in black

occurred at 2.5 sec delay time at all conditions with slight change at mold temperature of 50 °C.

At a higher delay time the water penetration decreased assumingly due to the melt solidification in the mold and thereby the inability of water to push the melt further out of cavity into the over-flow channel. Regarding the lower penetration at no delay time (delay time of 0 sec) it was observed that the injected water penetrated the melt surface, as well as inside it. This was due to very soft nature of the molten material where no time was given to form a solid skin. Consequently, the pressurized water was not able to apply full pressure into the melt core, and was damped out due to the loss of water on the surface. The effect was visible as a long sink mark close to the gate, shown in Fig. 2. These results in some way have a similar trend with results obtained for PP carried out in the previous works of the authors [3] but have some differences. Similarity is in the shape of relationship showing an optimum point (maximum penetration). However, the optimum point occurs earlier for ABS (at 2.5 sec) while the optimum point for PP occurres at 5 sec. Besides, it is observed that when the delay time is set to zero in ABS process, there is still penetration into the parts, although there is sink mark at the surface. But in the case of PP process and with delay time of zero, a deep long sink mark appeared on the part surface indicating too soft nature of the part. Hence, the WAIM process of ABS (an amorphous polymer) is more flexible and the process time can be set lower. Further comparison of the results for both materials (considering the following results) is

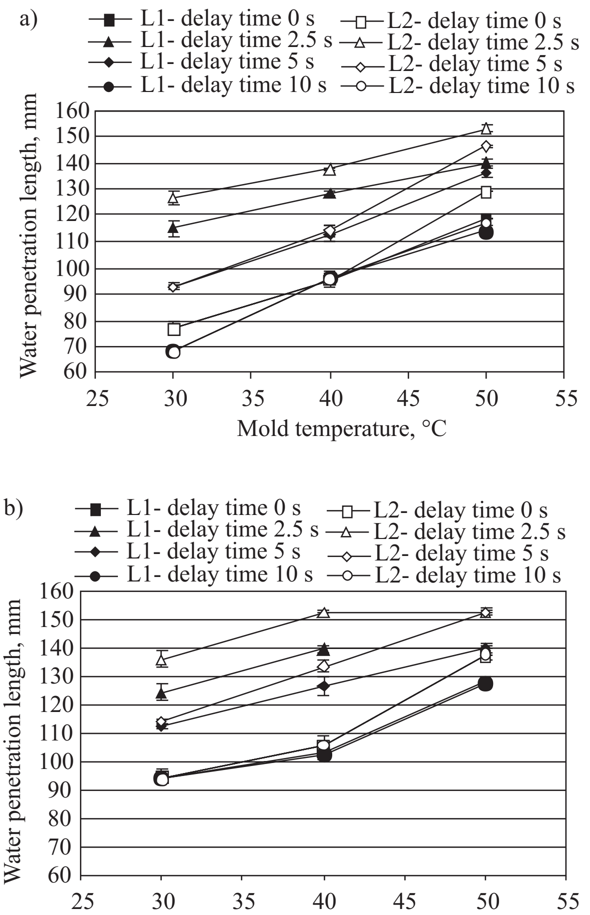


Fig. 3. Effect of mold temperature on water penetration at various delay times and holding times: (a) holding time of 5 sec, (b) holding time of 10 sec

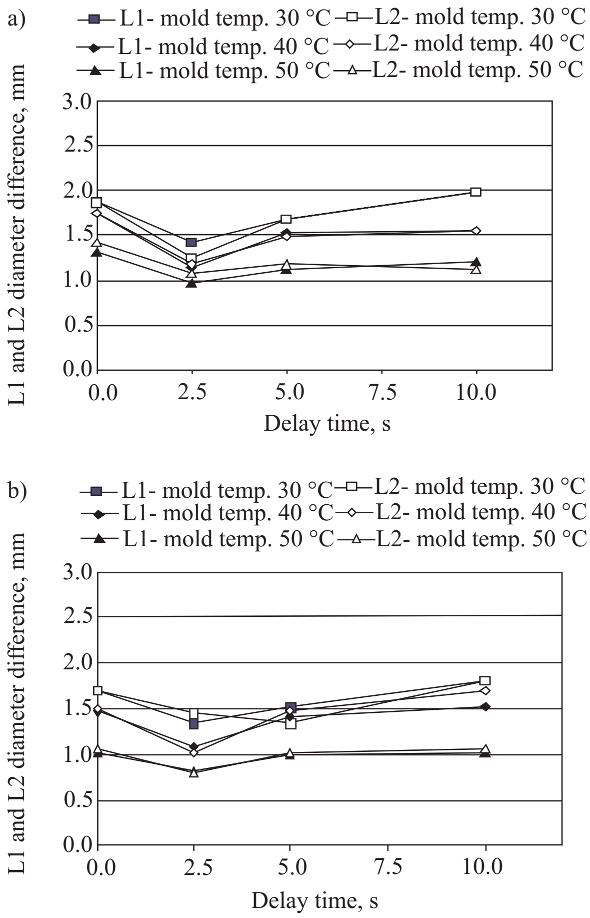
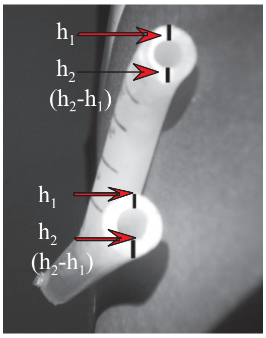
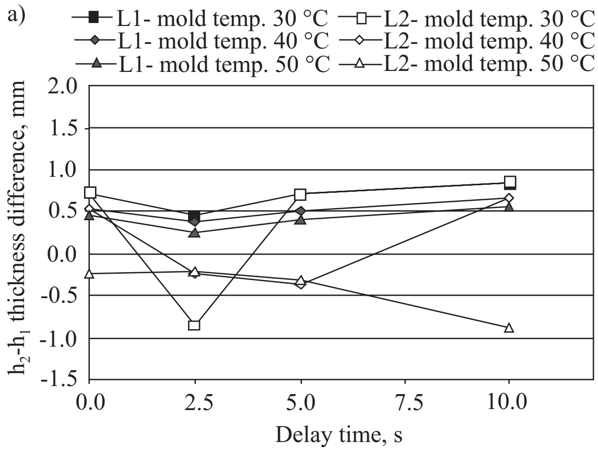


Fig. 4. Effect of delay time and mold temperature on hollowed core maximum and minimum diameter difference at various holding times: (a) 5 sec, (b) 10 sec





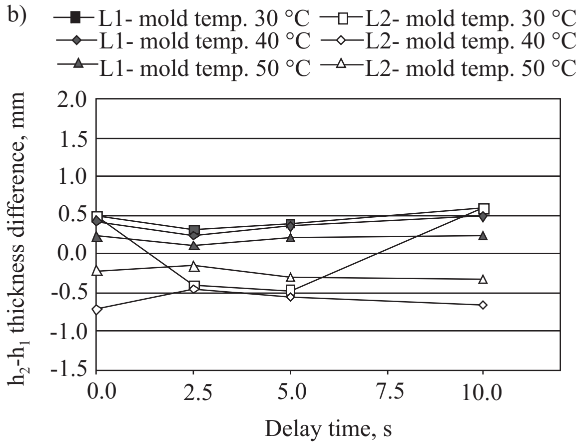


Fig. 5. Effect of delay time and mold temperature on residual wall thickness difference at various holding times: (a) 5 sec, (b) 10 sec

extensive and will be explored in details in future publication.

The effect of processing parameters on water penetration studied previously by Hwang *et al.* [9] showed that the water penetration monotonically increases with increasing water injection delay time with no extremum. However, they carried out their experiments with delay times of 1 to 5 sec (for ABS).

Figure 3 clearly illustrates the effect of mold temperature on the penetration. It is shown that with increasing the mold temperature the penetration length increases monotonically differently from the results obtained for PP where it tends to a *plateau*. The warmer mold causes lower heat loss of the polymer melt; consequently, the melt at higher temperature gives low resistance to the water penetration. It is interesting to note that while the penetration length decreases at longer delay time (10 sec), it tends to sharply increase when heating the mold from 40 °C to 50 °C. This tendency is less pronounced at lower delay times. As mentioned earlier, at longer delay time,

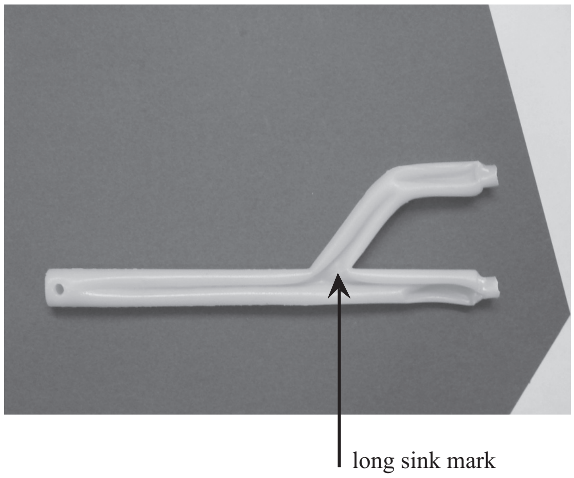
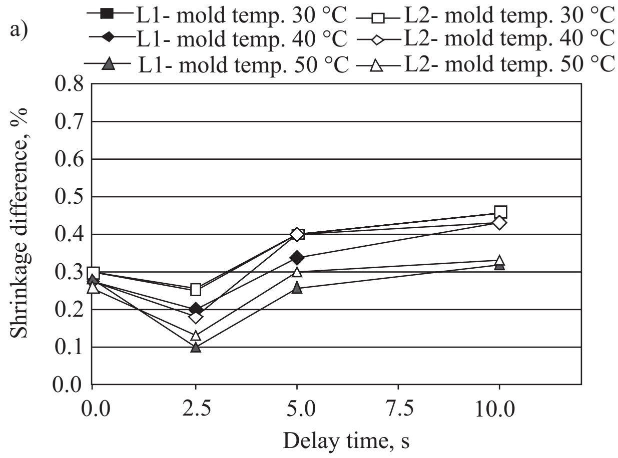


Fig. 7. A defect in the form of a sink mark along the surface of the hollowed cored part caused by high mold temperature 70 °C



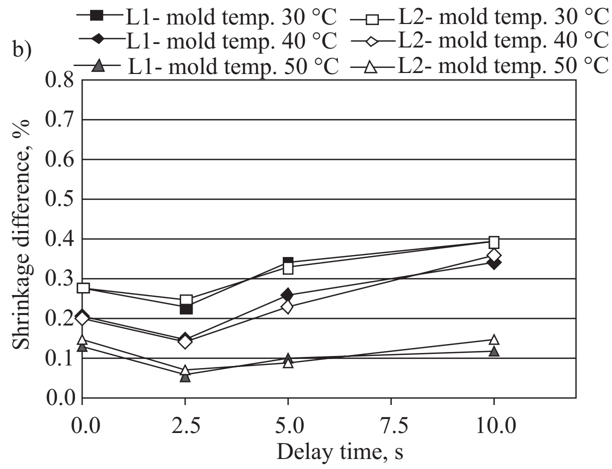


Fig. 8. Effects of delay time and mold temperature on maximum difference of shrinkage at various holding times: (a) 5 sec, (b) 10 sec

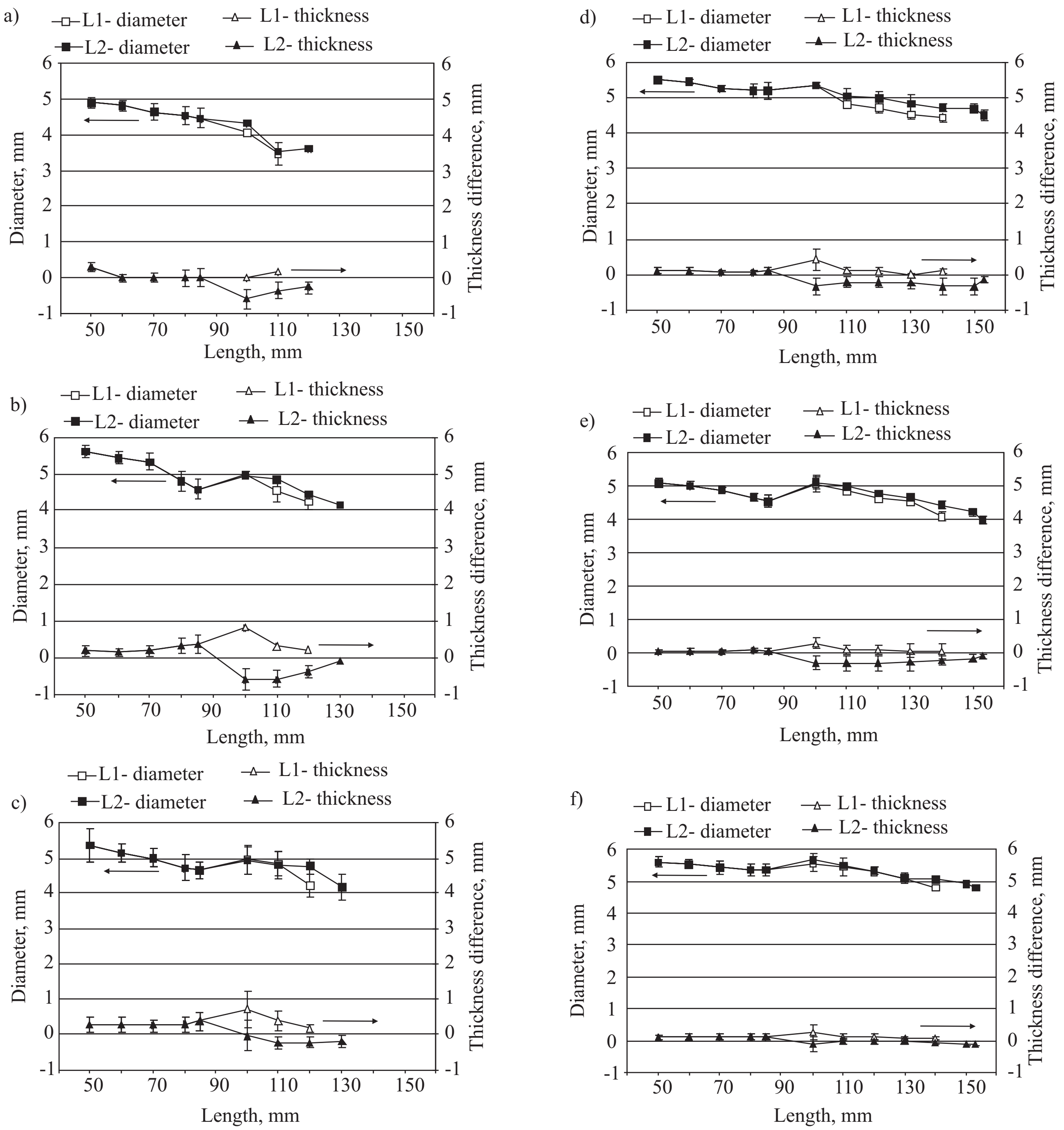


Fig. 6. Variation of residual wall thickness and hollowed core diameter along the pipe length at various holding times and mold temperatures: (a) delay time: 2.5 sec, holding time: 5 sec and mold temperature: 30 °C; (b) delay time: 2.5 sec, holding time: 10 sec and mold temperature: 30 °C; (c) delay time: 2.5 sec, holding time: 5 sec and mold temperature: 40 °C; (d) delay time: 2.5 sec, holding time: 10 sec and mold temperature: 40 °C; (e) delay time: 2.5 sec, holding time: 5 sec and mold temperature: 50 °C; (f) delay time: 2.5 sec, holding time: 10 sec and mold temperature: 50 °C

the heat loss gives rise to a more resistant melt causing a smaller penetration. Hence increasing the mold temperature could slow down heat loss and consequently causing a deeper penetration. At the lower delay time, since the time for the heat loss is too short, the effect of mold temperature is not highly pronounced compared to that of the longer delay time.

Figures 4 and 5 show the effect of delay time on the differences in maximum and minimum hollowed core diameter and residual wall thickness for both pipe heads; the former figure represents the uniformity of hole diameter along the cored channel and the latter one indicates the hole eccentricity. Due to the nature of the branched pipe, the eccentricities at both sides are generally in opposite directions. The results indicate that the more uniform core diameter and the lowest eccentricity occurred at the same delay time of 2.5 sec. For shorter and longer delay times a larger difference in residual wall thick-

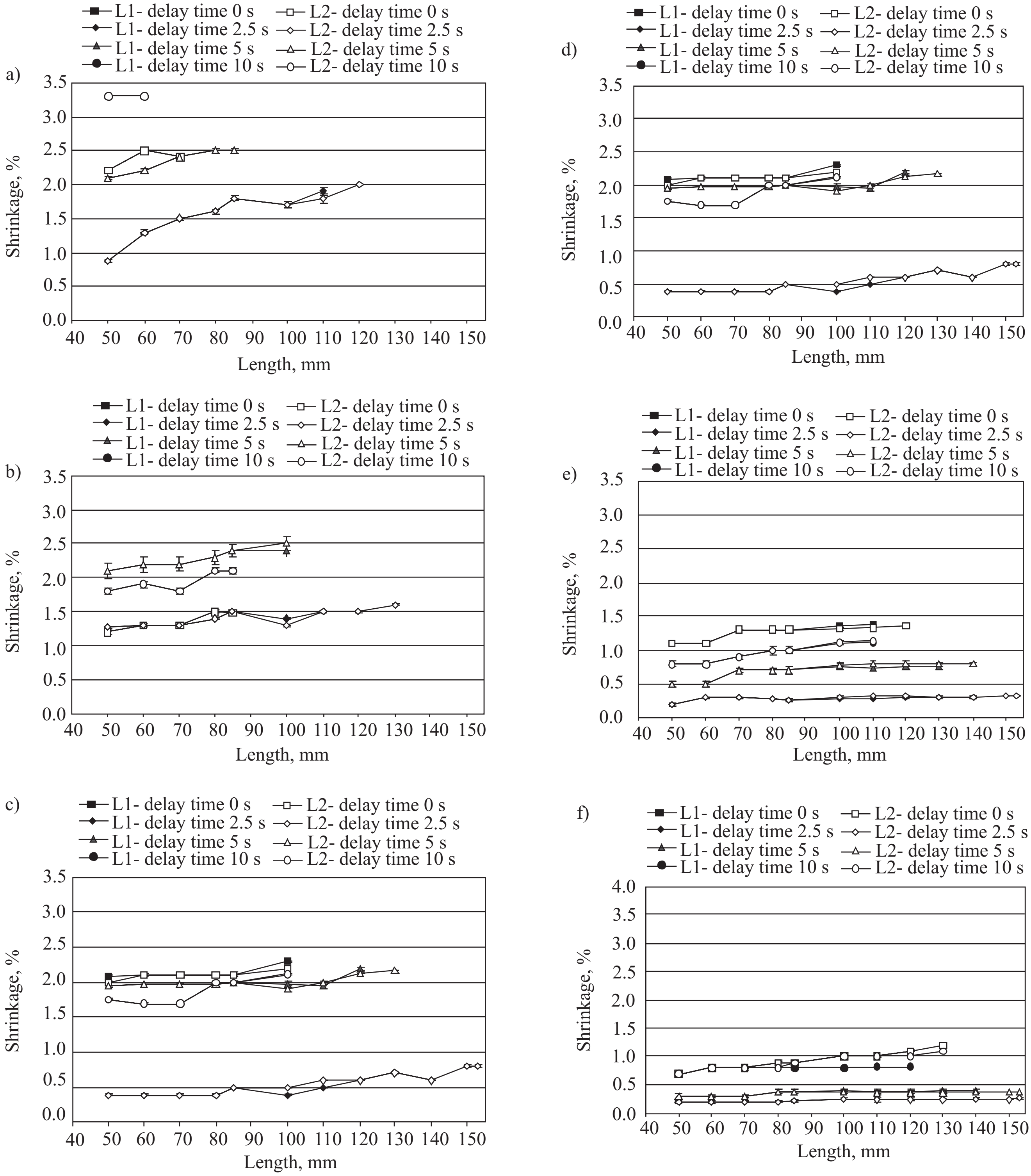


Fig. 9. Effect of delay time on shrinkage along the pipe length at both heads at various holding times and mold temperatures: (a) holding time: 5 sec, mold temperature: 30 °C; (b) holding time: 10 sec, mold temperature: 30 °C; (c) holding time: 5 sec, mold temperature: 40 °C; (d) holding time: 10 sec, mold temperature: 40 °C; (e) holding time: 5 sec, mold temperature: 50 °C; (f) holding time: 10 sec, mold temperature: 50 °C

nesses was observed. The reason seems to be the same as explained earlier.

Figure 6 illustrates the variation of core diameter and wall thickness differential along the pipe at the both pipe heads. The figures only state those samples produced at a delay time of 2.5 sec (the optimum condition).

The results clearly indicate that less variation in diameter and thickness occurred at a holding time of 10 sec and a mold temperature of 50 °C, while the delay time was set at 2.5 sec (Fig. 6f). At these conditions, a maximum penetration also occurred at both pipe heads. It must be mentioned that a maximum penetration can be achieved with lower holding time of 5 sec (at mold temperature of 50 °C) or lower mold temperature of 40 °C (with holding time of 10 sec). However, the variations in diameter and wall thickness differences are then larger. Considering that the maximum penetration reached in this study was the maximum possible penetration (the length of the pipe at two-heads), it is expected that the increasing the holding time or mold temperature could not improve penetration and only would cause an increase in cycle time.

Additional experiment was carried out with the mold temperature increased to 70 °C. The product revealed noticeable defect in the form of a long sink mark along the whole part as shown in Fig. 7. Hence, increasing the mold temperature could not improve the part quality, but it could considerably degrade it.

The molded part were sectioned and designated along their lengths shown in [3] in Fig. 3. The shrinkages of the part diameter (perpendicular to flow direction) at each section were measured (for both heads).

Figure 8a—b shows the effect of delay time on shrinkage at various mold temperatures and holding times. It clearly states that the minimum shrinkage occurs at a delay time of 2.5 sec, maintaining the other parameters unchanged. Figure 9 illustrates the shrinkage variation along the pipe length at both heads. It shows that at a longer holding time of 10 sec and a higher mold temperature of 50 °C, the low variation in shrinkage is observed (the same behavior as those of wall thickness and core diameter). The results also showed that, at all conditions, the minimum shrinkage occur at a delay time of 2.5 sec indicating a global optimum value to attain the best results. Increasing the delay time raised the shrinkage which is attributed to the weaker transmission of water pressure through a more viscous melt. It may be seen that the shrinkage for delay time of zero is the largest in most conditions which is due to the phenomenon presented in Figure 2.

Hence the optimum condition of processing could be suggested as the following: delay time of 2.5 sec holding time of 10 sec, and mold temperature of 50 °C.

CONCLUSIONS

The experimental investigation were carried out on the effect of processing parameters in WAIM process of a branched pipe (two-head pipe) using ABS as the polymeric material. Delay time, holding time and mold temperature were the selected processing variables. Water penetration (length), core diameter, wall thickness, and shrinkage were the output parameters to be measured. The results led to the following conclusions:

— An optimum delay time (here 2.5 sec) was found to produce a maximum penetration and a more uniform hole diameter along the pipe length with a minimum shrinkage. Too low holding time (here 0 sec) could promote a longitudinal sink mark on the product surface.

— A higher holding time (of 10 sec) produced improved quality of the product.

— A higher mold temperature (of 50 °C) was found to produce an improved product at the optimum delay time of 2.5 sec and at a high holding time of 10 sec. Further increasing the mold temperature produced a defective product with a longitudinal sink mark.

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