AHMAD ZIA AHMADZAI, AMIR HOSSEIN BEHRAVESH[*]

Tarbiat Modares University
Faculty of Engineering
Jalaal-e-Al-e-Ahmad ExpWay, P.O. Box: 14115-143
Teheran, Iran

An experimental investigation on water penetration in the process of water assisted injection molding of polypropylene

Summary — The water penetration phenomenon in the process of water assisted injection molding (WAIM) of a semi-crystalline polymer *i.e.* polypropylene (PP) was investigated. WAIM has been developed for production of hollow plastic elements and for parts having separate internal void spaces or channels. It offers a cost-effective means of producing the large elements having a good surface finish, reduced weight, and relatively short cycle time. In this study three processing parameters were investigated, namely, water injection delay time, holding time and mold temperature. Their effects on water penetration length, part hollow core characteristic (*e.g.* wall thickness, core diameter) and shrinkage were explored. The mold cavity shaped a branched pipe (two-head) to be cored out *via* water penetration. The results indicated that an optimum product, namely, having longer water penetration, lower wall thickness difference, more uniform pipe diameter and low shrinkage could be produced at a higher holding time, a higher mold temperature and at an optimum delay time.

Key word: water assisted injection molding, water penetration, hollow elements, delay time, holding time, mold temperature.

DOŚWIADCZALNE BADANIE PENETRACJI WODY PODCZAS FORMOWANIA POLIPROPYLENU W PROCESIE WTRYSKIWANIA WSPOMAGANEGO WODĄ

Streszczenie — Proces wtryskiwania wspomaganego wodą (WAIM) opracowano do produkcji z tworzyw polimerowych elementów mających puste kanały lub puste przestrzenie innego kształtu. Metoda ta pozwala na efektywne ekonomicznie formowanie, w stosunkowo krótko trwającym procesie, dużych elementów charakteryzujących się dobrym wykończeniem powierzchni i względnie mała masą. W ramach tej pracy badano wpływ na penetrację wody w uplastycznionym tworzywie znajdującym się w gnieździe formującym (rys. 1) i związaną z tym charakterystykę wytwarzanych elementów (np. grubość ścianki, średnica kanału, skurcz) trzech parametrów procesowych tj. opóźnienia wtrysku wody (czas upływający od rozpoczęcia wtrysku tworzywa ciekłego do momentu wtrysku wody, ang. *delay time*), czasu docisku (ang. *holding time*) oraz temperatury formowania (rys. 5—11, 13, 14). Badania przeprowadzono formując rozgałęzioną (dwuramienną) rurkę, której pusty rdzeń uzyskano dzięki penetracji wtryskiwanej wody (rys. 1—4). Stwierdzono, że produkt o najlepszej charakterystyce (tj. odpowiedniej długości penetracji wody w ciekłym polipropylenie, małej różnicy grubości ścianek, jednakowej średnicy kanałów i małym skurczu) uzyskuje się stosując dłuższy czas docisku (10 s), wyższą temperaturę formowania (50 ^{o}C) i średni czas opóźnienia wtrysku wody (5 s).

Słowa kluczowe: wtryskiwanie wspomagane wodą, penetracja wody, elementy puste, opóźnienie wtrysku wody, czas docisku, temperatura formowania.

Nowadays, plastic products are prevalent and diverse, produced by various plastics‘ technologies. Fluid assisted injection molding technology is one of the new approaches in this field. Because the technology has the advantages of fast production and automation, it let produce various highly precise parts and components of complicated forms. Therefore, it has become one the main production technologies in the plastics processing industry. When a gas is used as the fluid, the process is called gas assisted injection molding (GAIM). An inert gas such as nitrogen is introduced to produce a coreless part. Despite the high cost of the high-pressure unit and the high-pressure nitrogen which are required in the technology, the production costs are also greatly enhanced [1—2]. Water assisted injection molding (WAIM) process is one of the plastics manufacturing technologies which let produce both thick and thin parts with low shrinkage, warpage and sink mark. In the recent years, the WAIM technology has been reached an extensive at-

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[*] The author to whom the correspondence should be adressed: amirhb@modares.ac.ir

tention. This process has been developed at the Institute of Plastic Processing (IKV) in Aachen (Germany) [3].

The concepts of the WAIM technology and that of GAIM technology are similar. The manufacture procedure of both is first injection of the molten plastic into the mold, so as not filling it up completely but forming the condition of short-shot. Next, a pressurized liquid will be poured into the mold through the liquid injection nozzle to push forward the polymer until it fills up the mold cavity. The foremost advantage of the WAIM technology is the use of water as its actuating medium, which has a rather satisfactory cooling capacity and hence can substantially reduce the cooling time as well as the corresponding cycle time of the product and, as a result, will eventually enhance work efficiency. 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, low 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 [4]. Economically, as the established cost of implementing the WAIM technology is not too high and, especially, as it uses water as an actuating medium, the technology will substantially reduce the production cost, thus potentially enhance the industry's competition.

Kim *et al.* [5] developed a total system of liquid-gas-assisted injection molding (LGAIM) including a control unit (control of volume, pressure, and injection delay time of the liquid), a liquid-injection nozzle, a recipe of liquid system, and conducted part/mold design *via* computer-aided engineering (CAE) analysis. An applicable part, X-arm of a chair was used.

Liu and Chen [6] conducted a study on WAIM process of thermoplastic materials. The purpose of their research was to understand better the mold-ability of water assisted injection molded parts and to optimize the process.

Chang [7] worked on the complex flow behavior of the melt in WAIM process. He conducted the research by examining of the coupling effects of the process conditions and the material properties.

Liu and Lin [8] studied the fingering phenomenon in WAIM process of the composites. They used short glass fiber filled polypropylene (PP) as the polymeric material. They found out that the water pressure, delay time and shot size were the principle parameters affecting the formation of water fingerings.

Hwang *et al.* [9] studied WAIM process of a semicrystalline material (PP), and an amorphous material which was acrylonitrile-butadiene-styrene terpolymer (ABS). The processing variables were: melt temperature, water pressure, mold temperature, water injection delay time, shot size, and water temperature. Penetration length and hollowed core ratio were the output parameters.

Huang *et al.* [10] studied the effects of processing parameters on the difference in crystallization behavior between the beginning and the end of the water channel of the curved pipe analyzed using differential scanning calorimetry.

The current paper presents an experimental work on the effect of processing parameters on the penetration characteristics of penetrating water in a WAIM process of polypropylene as a semicrystalline polymer. The desired element was a branched (two-head) pipe for which a conventional tooling for injection molding could not be used. The purpose was to observe the effects of delay time, holding time and mold temperature on water penetration length, hollow core diameter, wall thickness difference, and shrinkage at both pipe heads.

EXPERIMENTAL

Materials

As a semicrystalline thermoplastic polypropylene (PP) supplied by Naved Zar Shemy (Iran) was used in the experiments.

Molding process

A laboratory injection molding machine (clamping tonnage of 70) was used to produce the elements. A mold was designed for the branched pipe and manufactured to contain an overflow channel (Fig. 1). This was to secure the complete filling of the cavity before water injection. Thus, the injected water pushes the melt into the overflow channel to make coreless part. The water injection nozzle was located at a distance of 10 mm from the gate (Fig. 1b).

A control unit was implemented consisting of 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 and holding times at the desired levels. A scheme of the system is shown in Fig. 2. During molding procedure three selected processing parameters were taken into account: delay time, holding time and mold temperature. Three different delay times were applied 2.5, 5 or 10 and two different holding times 5 or 10 s. Four values of mold temperature were used *i.e.* 20, 30, 40 or 50 ^{o}C. The total number of processes was 24 and processing conditions are listed in Table 1. To obtain reliable data, at least three experiments were carried out for each set of processing conditions after a steady process was reached.

The injection shot size was first adjusted to fill completely the mold cavity. A slight overflow was permitted

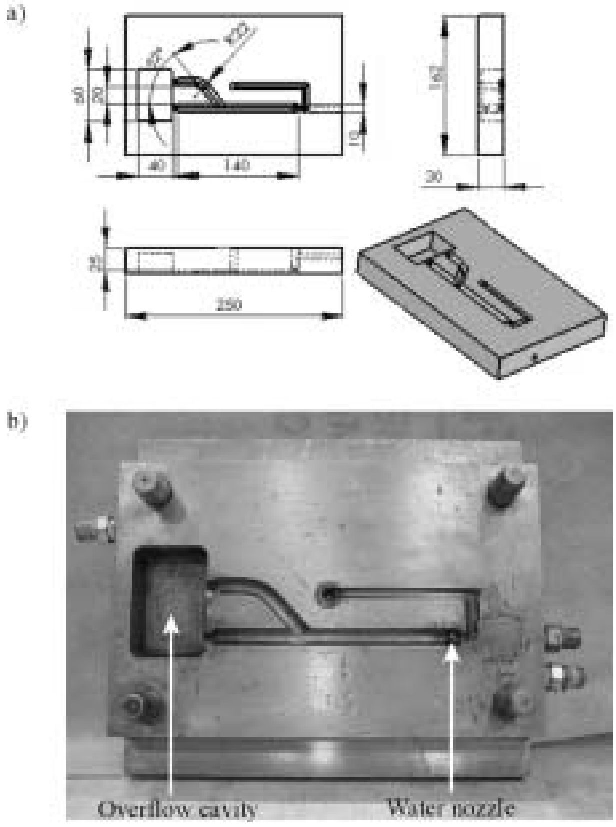

Fig. 1. Manufactured mold used in the experiments: a) layout of the mold cavity, b) the manufactured mold

to secure complete cavity filling. The shot adjustment was then maintained intact in all experiments. A micro-switch was then activated at the end of mold filling to transmit a signal to a timer, allocated for the delay time set at the desired value (while terminating the melt injection). After 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 penetrating into the melt to make coreless part. The holding pressure was then maintained for a determined time adjusted by the corresponding timer. When the holding time lapsed, the pressure was then released.

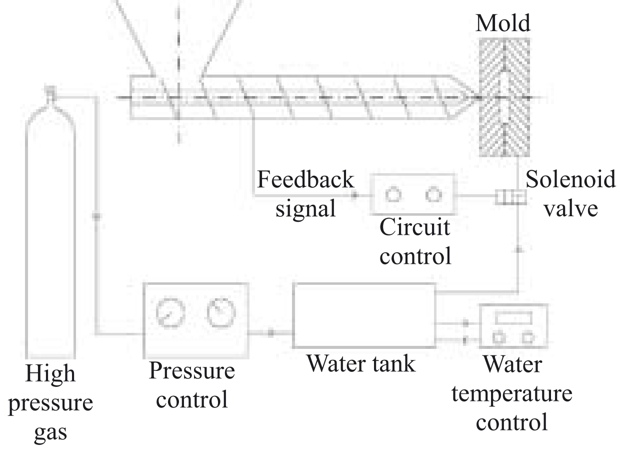

Fig. 2. Scheme of the water injection system

Table 1. Processing conditions selected for the experiments

Number of experiment	Delay time, s	Holding time, s	Mold temp., ^{o}C
1	2.5	5	20
2	5	5	20
3	10	5	20
4	2.5	10	20
5	5	10	20
6	10	10	20
7	2.5	5	30
8	5	5	30
9	10	5	30
10	2.5	10	30
11	5	10	30
12	10	10	30
13	2.5	5	40
14	5	5	40
15	10	5	40
16	2.5	10	40
17	5	10	40
18	10	10	40
19	2.5	5	50
20	5	5	50
21	10	5	50
22	2.5	10	50
23	5	10	50
24	10	10	50

The mold temperature was measured *via* thermocouples placed at 10 mm depth into the mold wall. The melt temperature was maintained and frequently checked with laser thermometer before injection. The melt temperature was fixed and found out to be 210 ^{o}C at all experiments.

The molded parts were sectioned and designated along their lengths. The selected sections start 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) as shown in Fig. 3.

The diameters of the hollowed cores and the maximum and minimum wall thicknesses (thickness diffe-

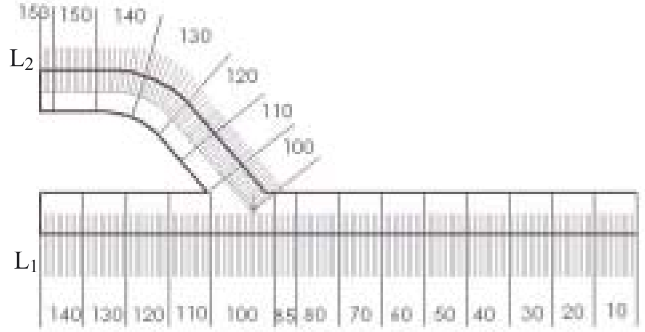

Fig. 3. Scheme of the scaling of the molded part

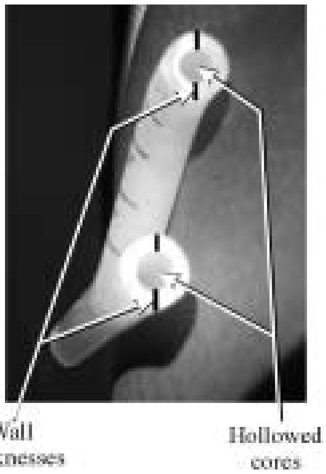

Fig. 4. Produced part showing the designated sections to be measured for wall thicknesses and inner diameters

rence) were then measured at each section (and for both heads) as shown in Fig. 4.

RESULTS AND DISCUSSION

The effect of delay time on water penetration at various mold temperatures and holding times is presented in Fig. 5. 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 occurred at 5 s of delay time at all conditions.

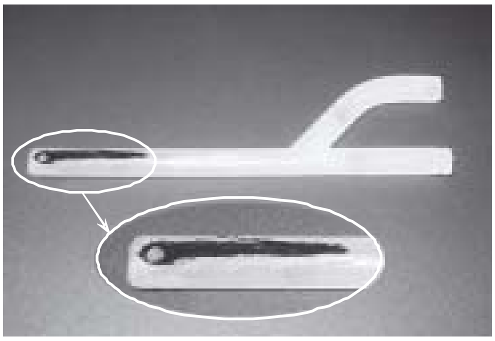

Fig. 6. Sample produced at a delay time 2.5 s showing a long sink mark close to the gate, marked in black

As the water injection delay time is increased above 5 s, the penetration length is decreased. This is due to increase in the cooling time before water injection and thus higher viscosity of the polymer melt so as higher resistance is imposed against water penetration. Regarding lower penetration length at the delay time of 2.5 s, it was observed that the injected water penetrated the melt surface as well as inside of the melt. This was due to too

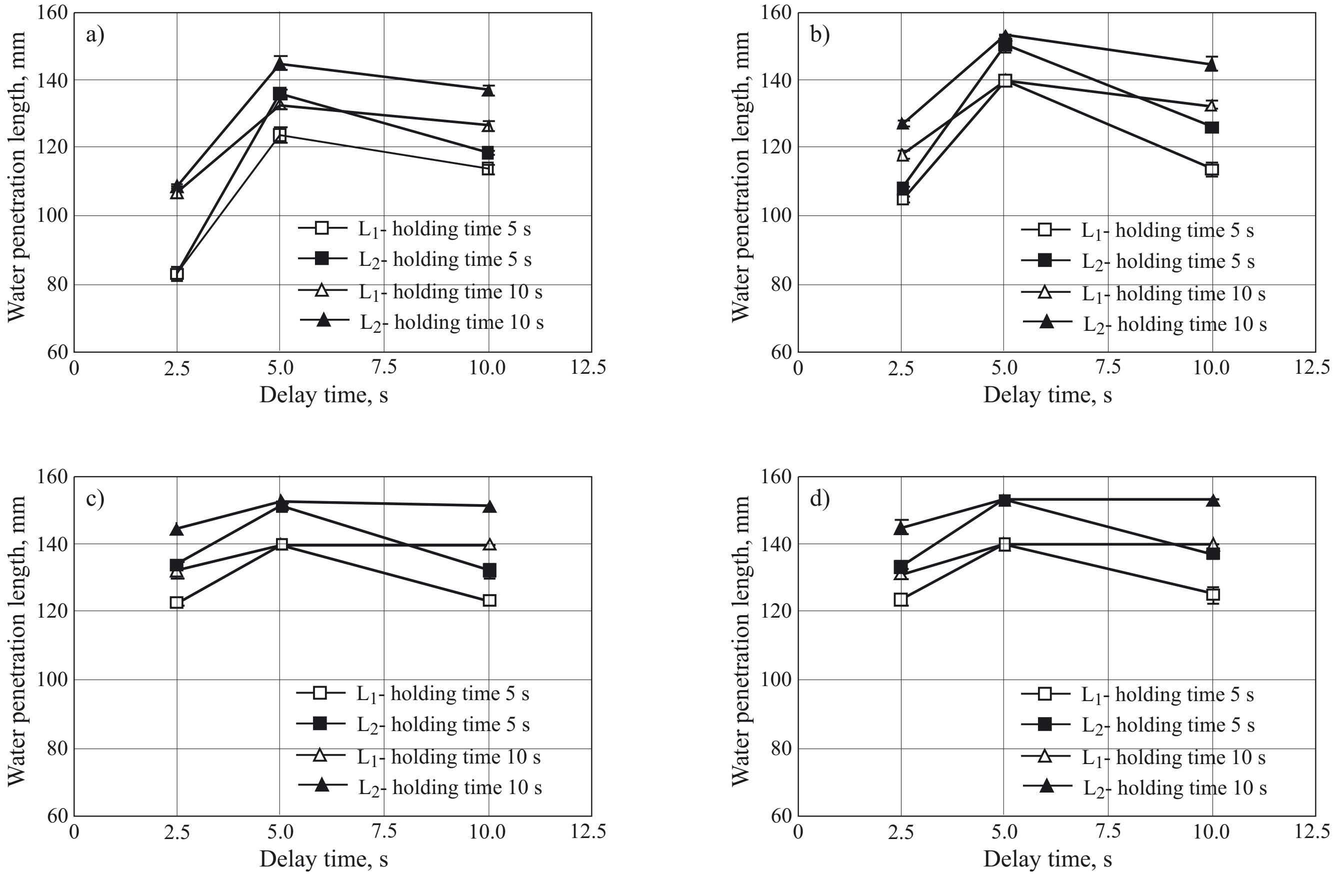

Fig. 5. Effects of delay time and holding time on water penetration length in the straight (L_1) and curved leg (L_2) of element at various mold temperature: a) 20 ^{o}C, b) 30 ^{o}C, c) 40 ^{o}C, d) 50 ^{o}C

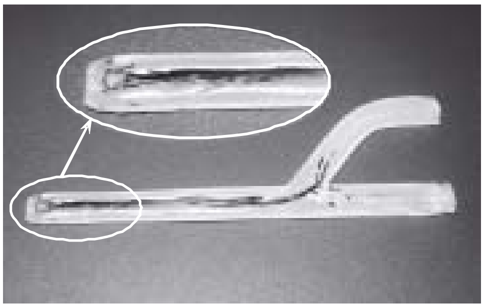

Fig. 7. Sample produced at a delay time 0 s showing a long sink mark, marked in black

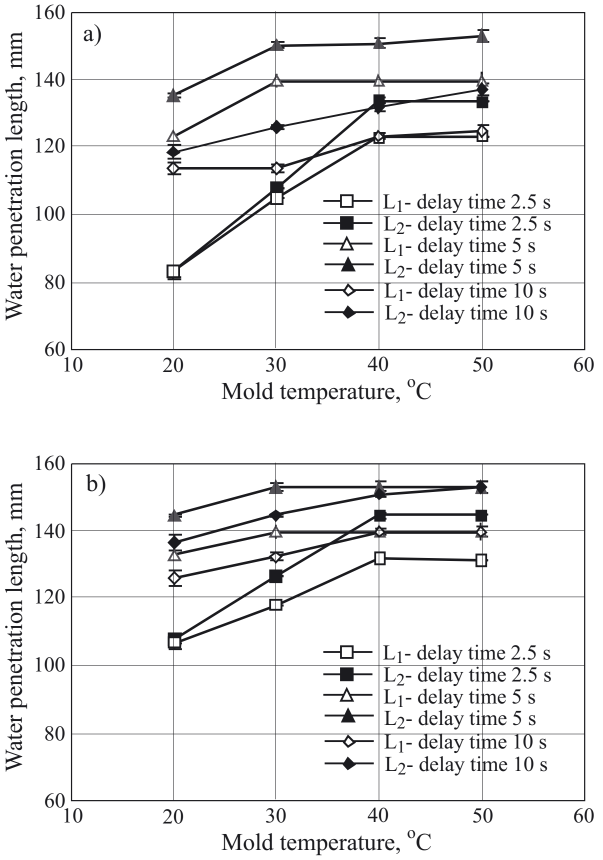

Fig. 8. Effect of mold temperature on water penetration at various delay times and holding times: a) 5 s, b) 10 s

soft nature of the molten material where low 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 appeared as a long sink mark close to the gate, shown in Fig. 6. It must be mentioned that when no delay time was set in the experiments, the produced element was not even hollowed by the water. In fact, the water flew on the surface so that it indented a long sink mark all along the surface of the element. The

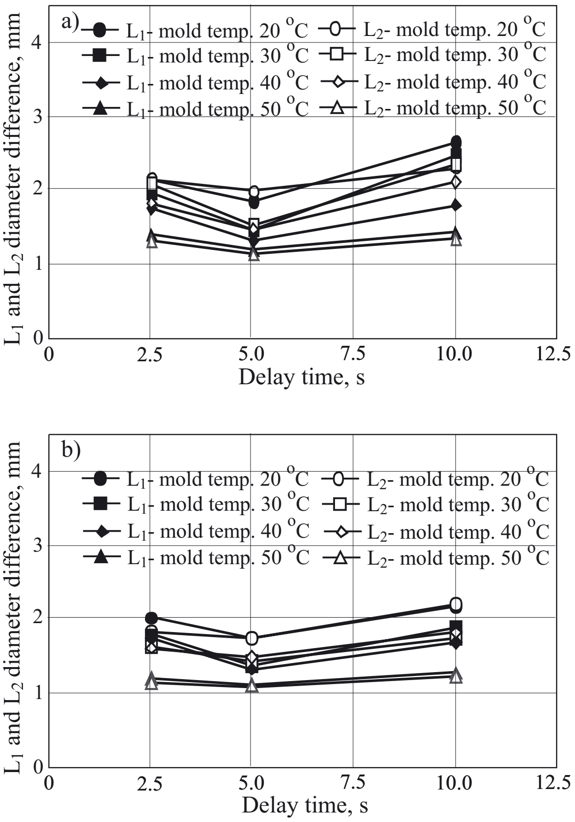

Fig. 9. Effects of delay time and mold temperature on hollowed core maximum and minimum diameter difference at various holding times: a) 5 s, b) 10 s

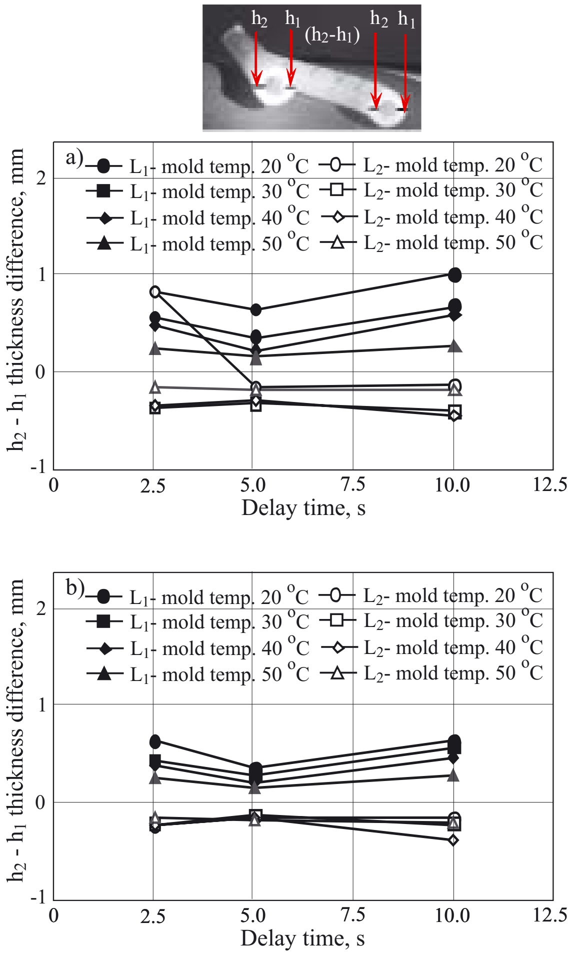

Fig. 10. Effects of delay time and mold temperature on residual wall thickness difference at various holding times: a) 5 s, b) 10 s

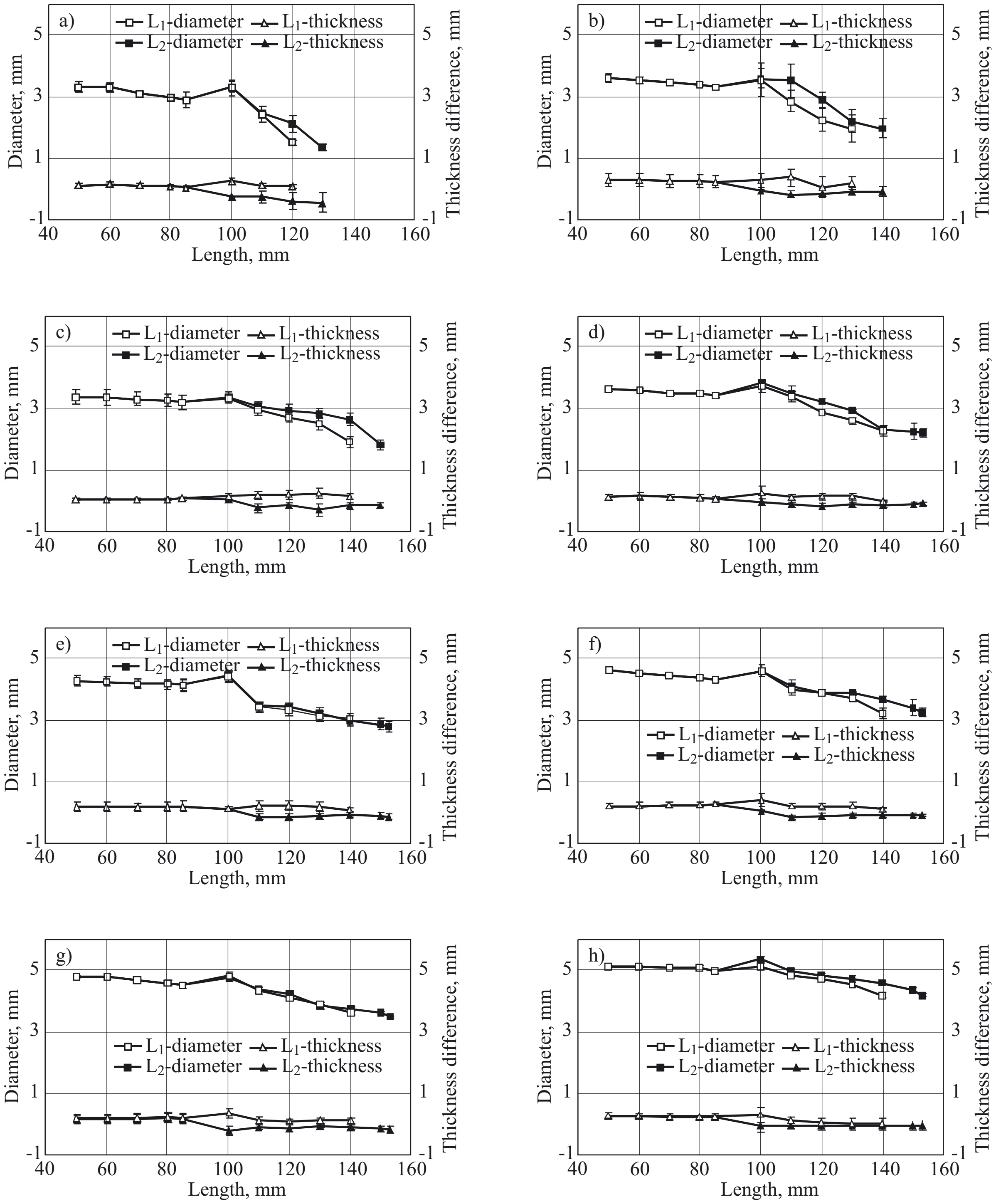

Fig. 11. Variation of residual wall thickness and hollowed core diameter along the pipe length at various holding times and mold temperatures respectively: a) 5 s, 20 °C; b) 10 s, 20 °C; c) 5 s, 30 °C; d) 10 s, 30 °C; e) 5 s, 40 °C; f) 10 s, 40 °C; g) 5 s, 50 °C; h) 10 s, 50 °C

element produced at delay time equal to 0 is shown in Fig. 7.

Hwang *et al.* [9] studying the effect of processing parameters on water penetration stated that when the delay time varied between 1 and 5 s (for PP), the water penetration increased with increasing delay time.

Figure 8 clearly illustrates the effect of mold temperature on the water penetration. It is shown that with increasing mold temperature the penetration length increases monotonically. The warmer mold causes lower heat loss of the polymer melt; consequently, the melt at higher temperature gives lower resistance to water penetration. It is interesting to note that the penetration length does not change with increasing mold temperature above 40 °C. Besides, the effect of mold temperature is more pronounced at a low delay time of 2.5 s.

It seems that when the mold temperature increases above a certain level, the heat loss slows down so that even at a long delay time (10 s) the melt temperature variation does not affect the viscosity of the melt. It is known that for a semicrystalline polymer, the melt viscosity at a temperature region well above the melting temperature does not change significantly. When the melt temperature approaches the melting point, a sudden change in viscosity occurs so that it becomes too stiff. Thus it is expected that the mold temperature above 40 °C keeps the melt temperature well above the material melting point.

Figures 9 and 10 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 first figure represents the uniformity of hole diameter along the core channel and the latter one indicates the hole eccentricity. Due to the nature of the branched pipe, the eccentricities at both sides are in opposite directions. The results indicate that the most uniform core diameter and the lowest eccentricity occurred at a delay time 5 s. However, it is noticed that at higher mold temperature the effect of delay time on these parameters is not significant.

Figure 11 illustrates the variation of core diameter and wall thickness difference along the pipe at the both pipe heads. The figures only state those samples produced at a delay time of 5 s (the optimum condition) show longer penetration, lowest hollow diameter and wall thickness variations.

The results clearly indicate that low variations in diameter and thickness occurred at a holding time of 10 s and mold temperature 50 °C, while the delay time was set at 5 s (Fig. 11h). It must be mentioned that the maximum penetration and hollow diameter can be reached at lower holding time 5 s (at mold temperature 50 °C) or at lower mold temperature equal to 40 °C. However, the variations in diameter and wall thickness differences are higher. Therefore, the longest holding time and higher mold temperatures are appropriate for the process. Considering that the maximum penetration reached in this study was the maximum possible penetration (the length of the pipe at two-heads), hence, it is expected that increasing holding time or mold temperature could not improve penetration and only would cause an increase in cycle time.

Additional experiment was carried out for mold temperature increased to 70 °C. The product revealed noticeable defect in the form of a long sink mark along the part surface as shown in Fig. 12. Hence, increase in the mold temperature could not improve the part quality, but it could considerably damage it.

Figure 13 shows the effects of delay time and holding time on shrinkage at various mold temperatures. The shrinkage difference represents the uniformity of outer diameter along the part length. It clearly states that the minimum shrinkage occurred at a delay time of 5 s, maintaining the other parameters unchanged. Figure 14 illustrates the shrinkage variation along the pipe length at both heads. It shows that at a longer holding time equal to 10 s and higher mold temperature 50 °C, the low variation in shrinkage is observed (the same behavior as those of wall thickness and core diameter).

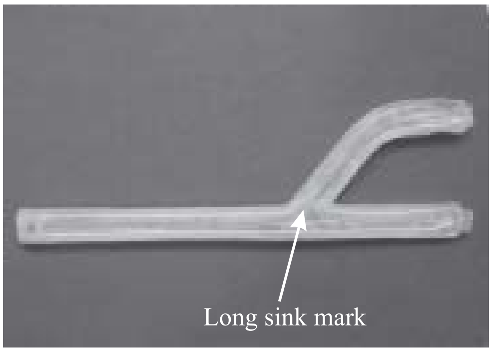

Fig. 12. A defect in form of sink mark along the surface of the hollowed cored part caused by high mold temperature 70 °C

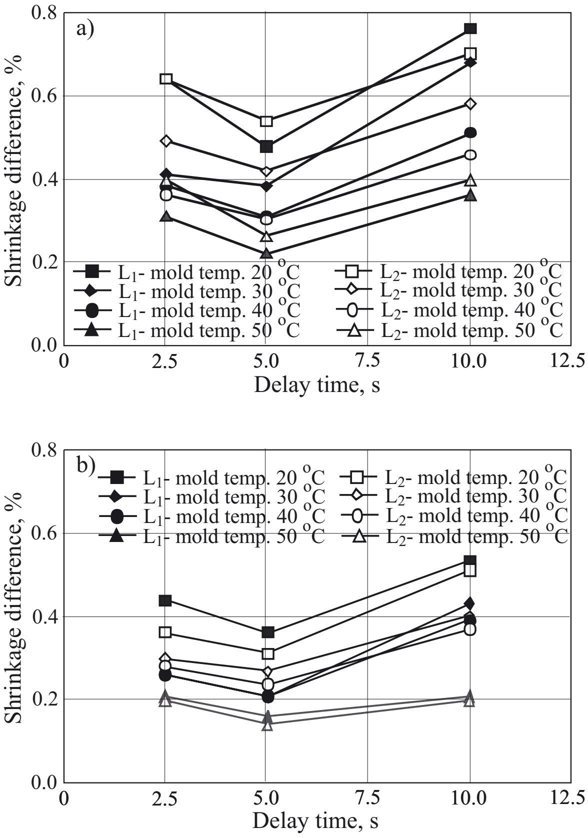

Fig. 13. Effects of delay time and mold temperature on maximum difference of shrinkage at holding times: a) 5 s, b) 10 s

Hence the optimum condition of processing could be suggested as: delay time 5 s, holding time 10 s, and mold temperature 50 °C.

CONCLUSION

The experimental investigations were carried out on the role of processing parameters in WAIM process of a branched pipe (two-head pipe) made of PP as the poly-

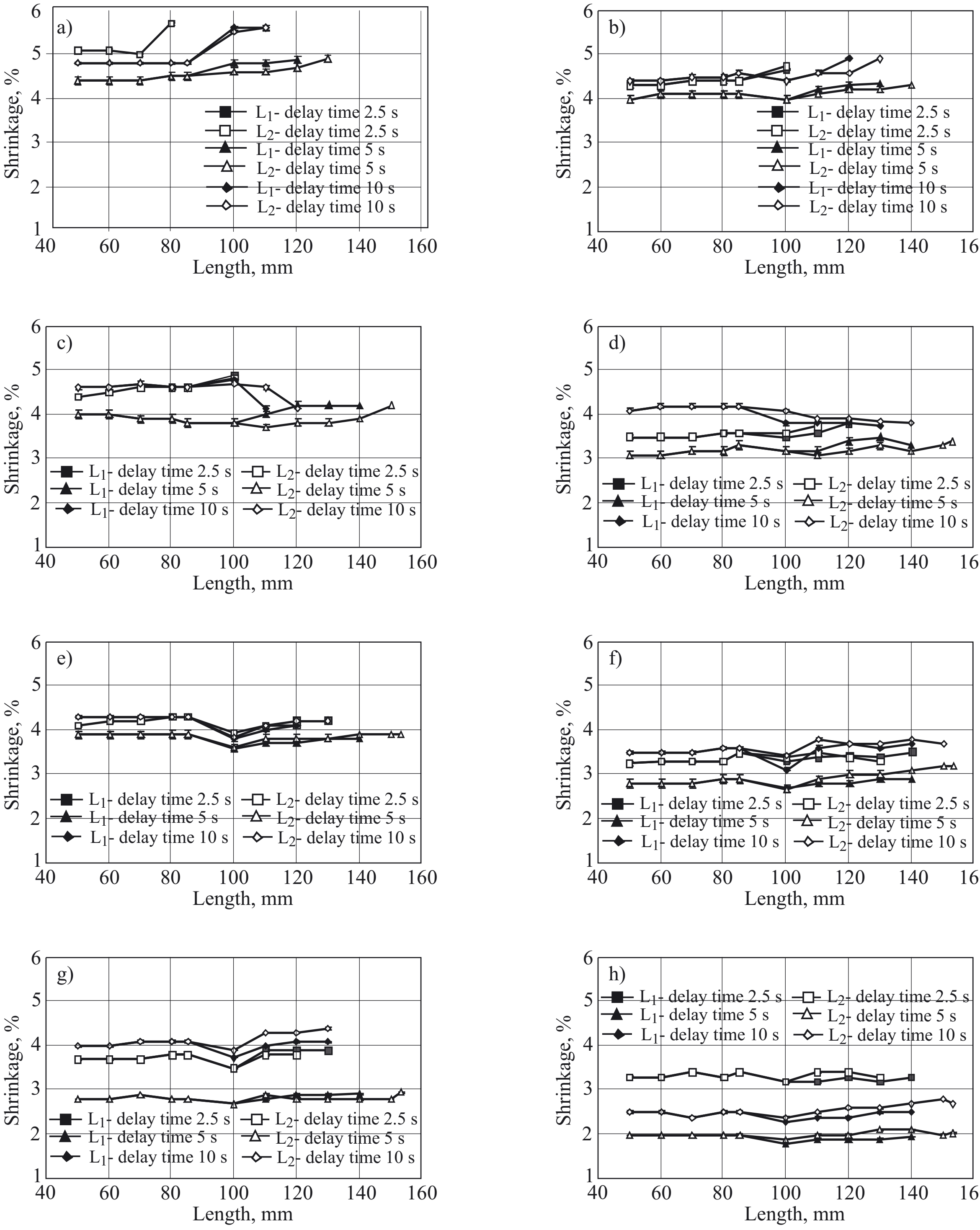

Fig. 14. Effect of delay time on shrinkage along the pipe length at both heads at various holding times and mold temperatures, respectively: a) 5 s, 20 °C; b) 10 s, 20 °C; c) 5 s, 30 °C; d) 10 s, 30 °C; e) 5 s, 40 °C; f) 10 s, 40 °C; g) 5 s, 50 °C; h) 10 s, 50 °C

meric 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 let conclude as follow:

— Delay time was the most effective factor influencing the penetration, hole diameter and shrinkage. The optimum delay time, here 5 s, was found allowing to produce the largest penetration, most uniform hole diameter, low hole eccentricity and a lowest shrinkage.

— At a higher holding time (of 10 s) the water penetration and core diameter uniformity decreased and the differences in thickness and shrinkage increased.

— A higher mold temperature (of 50 °C) was found allowing to produce an improved product at the optimum delay time 5 s and at high holding time 10 s. Further increase in the mold temperature produced defects in a product *i.e.* a longitudinal sink mark.

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Received 23 V 2008.