FLOW PATTERNS AND WATER PENETRATION IN WATER-ASSISTED MELT FILLING USING AN EMULATED MOLD*

Xu-Hui Liu[1, 2], *Han-Xiong Huang*[1**]

[1]**South China University of Technology, Guangzhou, People's Republic of China**

[2]**Yangtze University, Jingzhou, Hubei, People's Republic of China**

Abstract

Water-assisted injection molding (WAIM) provides a new way to produce hollow plastics parts and reduce production costs. The melt flow behavior when applying high pressure water has an important effect on the water penetration length and residual wall thickness of molded parts. So the purpose of this study was to visualize the flow patterns of melt and to characterize the water penetration behavior under applying high pressure water. The experimental setup mainly consisted of a water injection unit, a water injector, and an emulated mold. A circular mold cavity was filled alternately with red and green polymer tablets. The mold was heated long enough to make these tablets melt completely. After a delay time, water was injected into the melt to fill the cavity. The flow patterns of the polymer melt were visualized on the molded samples. The influences of process parameters on the melt flow, water penetration length, and residual wall thickness were investigated. The process parameters varied in experiments included initial filling, melt temperature, water delay time, and water pressure. It was demonstrated that the initial filling was the most significant factor affecting the water penetration.
Keywords**:** Polymer, Water-assisted melt filling, Flow patterns, Water penetration

Introduction

Water-assisted injection molding (WAIM) is a new technology to produce hollow plastics parts. The benefits of the process have been commercially realized for about six years [1]. It has been used for the production of tube parts, bent parts, flat parts with struts, and complex parts consisting of both thin and thick sections [2]. Compared with the conventional injection molding, WAIM can substantially reduce material costs, clamp tonnage, and cycle time. Product quality can be improved by reducing sink marks, residual stress, distortion, and warpage that are normally encountered in conventional injection molding. It also allows more freedom in the design and manufacture of plastics parts [3].

In WAIM, the mold cavity is partially filled with polymer melt followed by the injection of water into the core of the melt. It is a complicated process, because of more process parameters involved and the dynamic interaction between the water and polymer. WAIM is a relatively new technology, and only limited experimental studies have been conducted to understand the characteristics of the molding process [3–7]. Many unknowns remain concerning the melt flow phenomenon under applying high pressure water. Therefore, it is important to understand that behavior.

In this work, the melt flow patterns during water-assisted melt filling were studied using a water injection molding system newly-developed in our lab. An experimental study, based on the orthogonal

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** Corresponding author. *E-mail address*: mmhuang@scut.edu.cn.

array design, was conducted to characterize the effect of different process parameters on the water penetration behavior. Water penetration length and residual wall thickness were measured on the samples.

Experimental

Material

The material used in experiments is a general-purpose polypropylene (PP), grade CJS700 from Sinopec Group Guangzhou Co. Ltd. Its melt flow index is about 8.35/10min (at 230℃ and 2.16 kg).

Experimental Apparatus and Methods

Figure 1 schematically illustrates the experimental setup used in this work. The setup consisted of a water injection unit, a water injector, an emulated cylinder mold, mold temperature controller, and so on. The emulated mold (as schematically shown in Figure 2) was closed by a bottom cover equipped with a shut-off water injector (to prevent the polymer melt flow into injector) and a top cover containing an air vent. The mold cavity had a length of 136 mm and a diameter of 18 mm. The mold temperature was sensed and controlled by thermocouple-actuated units. Three thermocouples were mounted in the cylinder mold. The mold was heated by heater and cooled by pumping oil through six holes, which were drilled in the cylinder along axial direction at equiangular (60°) intervals.

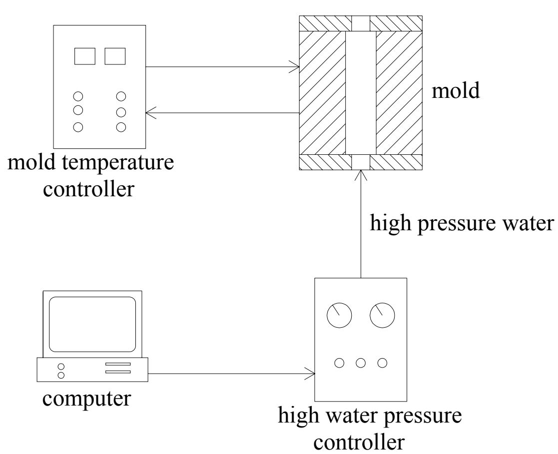

Figure 1. Schematic of the Experimental Setup

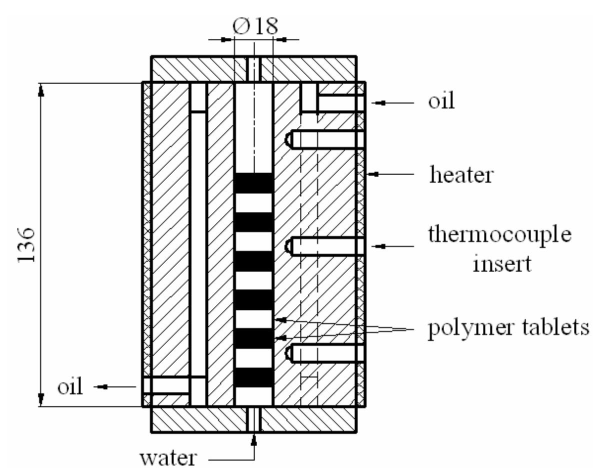

Figure 2. Cylinder Mold for Water Injection Molding (unit: mm)

In experiments, the mold cavity was filled alternately with 5 mm thick red and green tablets of PP, which were prepared by sawing red and green rods that were injection molded. The mold was heated for about 90 min to make the PP tablets melt completely. Then the high pressure water was injected into mold through the shut-off injector. After the mold was cooled sufficiently by oil, the sample was pushed out of the cavity and sawed in half. The polymer flow patterns were then visualized. The water penetration length and the residual wall thickness on the sample were measured with a precision caliper. The latter was measured in the middle location of the primary water penetration zone.

Experimental Parameters and Design

The experiments were conducted under different conditions, including initial filling, melt temperature, water delay time, and water pressure. Among them, initial filling referred to the percentage of volume of polymer tablets filled in the mold cavity to the volume of cavity. Water delay time was measured from the time when mold heating was stopped to the instant when water was introduced into polymer melt.

The molded specimens were then used to determine the penetration behavior of water into the polymer melt. An orthogonal array design of experiment was used to evaluate the significance of above-mentioned process parameters on the water penetration length and residual wall thickness. A three-level orthogonal array, which was arrayed from a low value to a high value as shown in Table 1, was chosen. The levels of the process parameters and the experimental array used are shown in Table 2.

Table 1. The Levels of Factors Used in Experiments

Factors	Level		
	1	2	3
A: initial filling (%)	58.8	66.2	73.5
B: melt temperature (℃)	180	200	220
C: water delay time (s)	30	90	150
D: water pressure (MPa)	4	6	8

Table 2. L9 (3^4) Orthogonal Array Used in Experiments

Trial no.	Factors			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Results and Discussion

Melt Flow Pattern

Photographs of melt flow pattern and water channel on the molded samples are shown in Figure 3. As can be seen, there is a mark between primary water penetration and secondary water penetration zones. It is interesting to note that the latter exhibited a "∧" shaped channel in the specimen.

As it can be seen, the melt flow under applying the high pressure water exhibits a "∧" shaped pattern. At lower initial filling, the fountain flow phenomenon can be identified, as shown in Figures 3(a) and (b). This phenomenon can be briefly explained as follows. It is evident that water penetrates along the path with the lowest resistance and pushes the core melt to advance. Melt front is broken through, stretched outward toward the side wall and dragged back with the wall. Under higher initial filling, the melt front is broken through and stretched along the wall, but fountain flow phenomenon does not appear, as shown in Figure 3(c).

(a) F=58.8 (b) F=66.2 (c) F=73.5

Figure 3. Melt Flow Pattern in Different Conditions
F: initial filling (%)

Effect of Process Parameters on Water Penetration Length

Water penetration length under different process parameters is shown in Table 3, in which the range (R) is also listed. The range is defined as the difference between the upper limit of the maximum observed score and the lower limit of the minimum observed score [8]. The larger the value of R is, the more important that parameter is in influencing the process response. Therefore, the significance of process parameter on the water penetration length can be judged by the value of R in Table 3.

Based on the analysis of range in Table 3, the relative significance of process parameter on the water penetration length is arranged in the decreasing order of initial filling (R=29.14), melt temperature (R=21.62), water delay time (R=12.44), and water pressure (R=7.17). Figure 3 shows the variation trend of water penetration length under different process parameters.

The experimental results suggested that the initial filling was the most significant factor for water penetration. As initial filling increased, water penetration length obviously decreased. This is because that there was less space for water to inject and penetrate into the melt at a higher initial filling. The melt temperature was found to be the second important parameter affecting the water penetration length. However, Figure 4 shows a "∧" shaped response for melt temperature. It was observed a minor decrease in water penetration length when increasing the water pressure.

Effect of Process Parameters on Residual Wall Thickness

The values of residual wall thickness under different process parameter and corresponding ranges (R) are listed in Table 4. Figure 5 is a graphical representation of the experimental results.

Table 3. Water Penetration Length

Trial no.	Factors A	B	C	D	Water Penetration Length (mm)
1	1	1	1	1	110.20
2	1	2	2	2	131.86
3	1	3	3	3	107.28
4	2	1	2	3	91.10
5	2	2	3	1	107.46
6	2	3	1	2	106.18
7	3	1	3	2	68.66
8	3	2	1	3	95.52
9	3	3	2	1	97.76
∑(1)/3	116.45	89.99	103.97	105.14	
∑(2)/3	101.58	111.61	106.91	102.23	
∑(3)/3	87.31	103.74	94.47	97.97	
R	29.14	21.62	12.44	7.17	

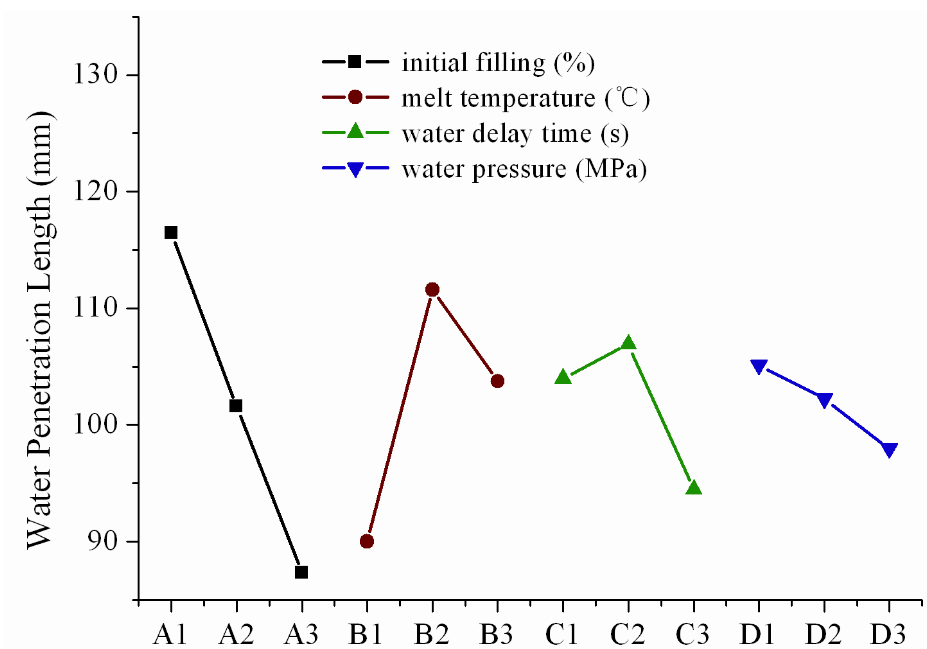

Figure 4. Effects of Factor on Water Penetration Length

Table 4. Residual Wall Thickness

Trial no.	Factors A	B	C	D	Residual Wall Thickness (mm)
1	1	1	1	1	2.95
2	1	2	2	2	2.74
3	1	3	3	3	3.04
4	2	1	2	3	2.55
5	2	2	3	1	2.84
6	2	3	1	2	2.72
7	3	1	3	2	3.36
8	3	2	1	3	1.58
9	3	3	2	1	2.92
∑(1)/3	2.91	2.95	2.42	2.90	
∑(2)/3	2.70	2.39	2.74	2.94	
∑(3)/3	2.62	2.89	3.08	2.39	
R	0.29	0.56	0.66	0.55	

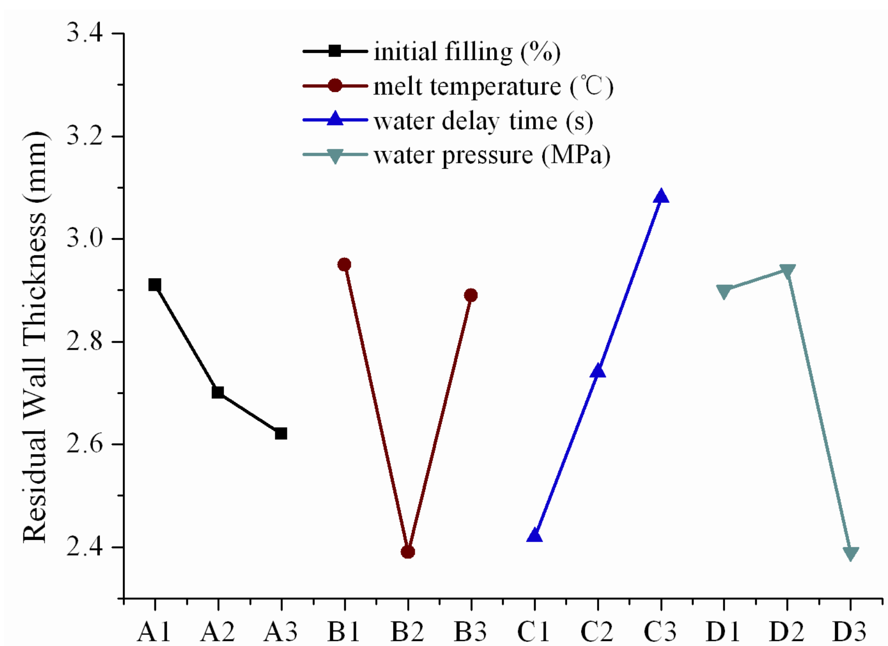

Figure 5. Effects of Factor on Residual Wall Thickness

The values of R showed that melt temperature and water pressure had the almost same degree of significance on the residual wall thickness. Their influences were lower than water delay time and higher than initial filling. The residual wall thickness increased with increasing water delay time and decreasing initial filling. However, Figure 5 shows a "∨" shaped response for melt temperature, and a "∧" for water pressure.

Conclusions

A newly-developed water injection system and emulated mold were used to investigate the melt flow patterns and water penetration behavior during the melt filling. The studies demonstrated that the fountain flow phenomenon was seen under lower initial filling. Moreover, initial filling was the most significant factor affecting the water penetration length. An increase in initial filling led to a decrease in the water penetration length. The water delay time was the most important factor for residual wall thickness. An increase in water delay time resulted in a larger residual wall thickness.

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