Visualization of the Flow History Contours at the Cross-Section of a Weld-Line in an Injected Molded Part

Saeed Fathi, Amir Hossein Behravesh

Faculty of Engineering, Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran

Received 8 July 2007; accepted 13 January 2008
DOI 10.1002/app.28113

ABSTRACT: This article presents visualization of flow history contours at the cross-section of an injection molded part along the weld-line originated by an obstacle pin in a plate-shaped cavity. The visualized flow history contours unveiled the interface of the two adjacent flows through which the penetration of one flow front to the other at the interface was observed. The penetration which was the most at the core of the part behind the obstacle pin was inferred to be originated from an eccentricity in the position of the obstacle pin. Applying image processing techniques, a sequence of the variation in the shape of the interface along the weld-line was extracted from which the amount of penetration at different distances behind the obstacle was measured. Experimental results revealed an oscillation in the direction of the penetration along the weld-line at the core of the part. A scanning electron microscope micrography was also applied to characterize the V-notch along the weld-line at the surface of the molded part. V-notch characterization was used to investigate the possible correlation between the internal and external behaviors of the molten plastic during weld-line formation by which an obstruction affected zone at the weld-line area behind the obstacle pin was distinguished. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 412–417, 2008

Key words: weld-line; V-notch; flow history contours; visualization; injection molding; imaging; interfaces

INTRODUCTION

Injection molding is one of the most important polymer processing methods for mass production of polymeric products. There are many attractive aspects for the research in this process; one of them is ''weld-line,'' which is categorized as a defect in molded parts, although in many cases its existence is inevitable. Weld-line is formed during filling stage when melt front is dissected by a flow obstruction and then reunited. The attributed weakness due to the weld-line is a result of a change in macroscopic and microscopic structures at the interface as a consequence of the flow and thermal history during injection molding.[1] In addition, different cooling behaviors and poor bonding at the interface of two adjacent flows shape a V-notch just behind the obstruction, which contribute to the further weakness of the weld-line. Studying the flow behavior at the interface of two adjacent flows can give an insight into the mechanism of weld-line formation. A better understanding of such a mechanism could help design a quality molded part.

Some attempts have been made to study the mechanical properties of nonuniform weld-lines formed behind an obstacle pin via measuring tensile strength or fracture toughness.[2–4] As a result, a variation in the mechanical properties along the weld-line was reported. At the region closer to the obstruction point, the material strength is lower than that of farther region. In addition to the total weakness of the weld-line, the known variation in mechanical properties along the weld-line has initiated researchers to study the flow behavior and find the main sources of the mechanical weakness which were classified as (i) lack of molecular entanglement, (ii) flow-induced orientation at the interface, and (iii) formation of the V-notch at the surface of injection molded parts.[5,6]

It is known that the poor bonding of the surface layers of a part, which includes V-notch, is a result of insufficient time for polymer molecules to diffuse across the interface.[7] This variation along the thickness direction was experimentally verified by a microhardness study along the cross-section of a weld-line.[8] Results showed that the core of the part is stronger than the surface layers. In addition, a homogenous material with no presence of weld-line was found at the further distances from the obstacle pin, attributed to the effective interdiffusion.

This article presents a novel technique by which the flow history of a polymeric melt is visualized at the cross-section of a weld-line in an injected molded part. The shape and position of the flow fronts interface along the thickness direction were studied and

---

Correspondence to: A. H. Behravesh (amirhb@modares.ac.ir).

Journal of Applied Polymer Science, Vol. 109, 412–417 (2008)

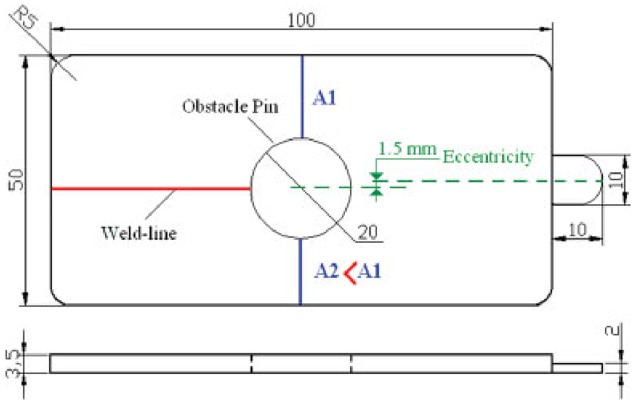

Figure 1 A schematic design of the cavity and the eccentricity of the obstacle pin (dimensions in mm unit). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

quantified via inspecting flow contours at the cross-section. The measured quantities, along with the V-notch angle, were depicted versus the distance along the weld-line to investigate a probable correlation in material behavior between the internal (core) and external (surface) of the molded part.

EXPERIMENTATION

Materials and equipment

Acrylonitrile-butadiene styrene (ABS) resin, grade 750, produced by Kumho Chemical (Seoul, Korea), was used as the polymeric material. A mold was designed and manufactured to produce plate-shaped parts with dimensions $100 \times 50 \times 3.5$ mm^3 in a conventional 70-ton injection molding machine. An obstacle pin of 20 mm in diameter at the middle of the mold cavity was mounted to produce a weld-line during mold filling. As shown in Figure 1, the obstacle pin had a vertical eccentricity of 1.5 mm giving an unequal cross-section of the cavity at the region ($A1 > A2$). The cavity was machined off-center to allow melt enter from the side.

Procedure

Injection molding machine was set and prepared to inject ABS resin at the recommended conditions given by the material supplier. The melt temperature was accurately measured before injection using an infrared thermometer on an accumulated molten bulk injected in air. The melt and mold temperatures were found to be about 235°C and 35°C, respectively, in all experiments. The melt was then injected into the mold with a flow rate of 7 cm^3/s and injection pressure of 25 MPa. For visual mold safety, no holding pressure was applied. Although the molten material entered the cavity through the gate, it advanced to fill the cavity, till the flow front reached the obstacle pin. The flow front was then divided into two fronts. By passing the obstacle pin, the two adjacent fronts collided with each other behind the pin and the two adjacent flows started to merge and formed a weld-line. After filling the cavity, 20-s cooling time was considered to open the mold and remove the injected part.

As mentioned earlier, the objective of this study was to investigate the plastic material behavior in the core of a weld-line formed behind an obstacle pin. Thus, at various distances from the edge of the hole, and along the weld-line, sections were cut perpendicularly to investigate the material behavior induced by flow at the cross-section of the molded part. The cutting tool was a microtome (Buehler, Lake Bluff, IL) and the location of cuts is shown in Figure 2. The cutting speed was set at 6 rpm. A light micro-photography was applied to picture the visualized contours for further analysis using a digital camera (Canon, Model G6 with 7.1 M Pixel resolution) on a microscope (Leica, Model: Wild M8). The high resolution micro-photographs were transferred to a computer for image processing using appropriate software.

The flow history in the core of the molded part could be studied if some contours due to a color change at the cross-section are created. The interface line was tracked and highlighted for each section so that its shape and position was visualized. This could reveal the variation of the interface position in the core of the part along the weld-line. This variation was studied quantitatively by measuring the penetration depth (of the interface) from one front to the other at different distances behind the obstacle pin. The position of the V-notch was also distinguished in the micrographs at different distances

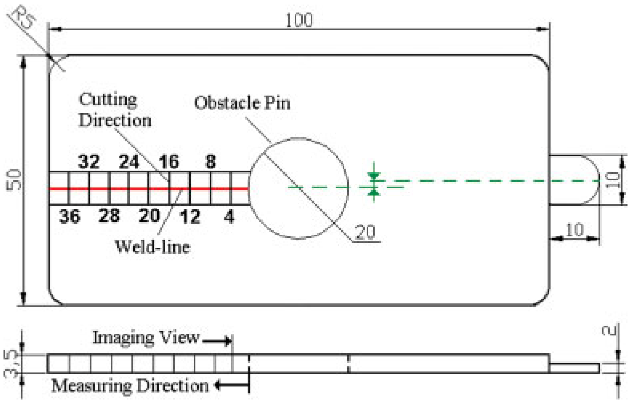

Figure 2 Details of the injection molded part and sample preparation for micro-photography (dimensions in mm unit). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

behind the obstacle pin. In addition, a scanning electron microscope (SEM) micrography on the cross-section of the part was accomplished to measure the variation of V-notch angle along the weld-line to study its conformity with the material behavior in the core of the part.

RESULTS AND DISCUSSION

Visualization of flow history contours

The preliminary attempts to obtain flow history contours revealed no result. However, when varying the conditioning of the granules, some contours of flow history at the cross-section of the weld-line were observed. The principle variation in conditioning was that the drying step was omitted for granules before injection. Previously, the ABS granules had been dried in an oven at 75°C for 3 h before injection.

Figure 3 reveals a clear visualization of flow history contours at a distance of 4 mm behind the obstacle pin, along the weld-line. As it is seen, there is a color contrast on the surface of the cross-section which is attributed, here, to the flow history contours. These contours were clearly observed in all samples.

It should be mentioned that the visualization of such contours was also effected by the cutting conditions. No clear visualized contour was observed at the cross-section of the molded part using a simple plastic cutter (knife) or scissor. Counters were observed when using a rotary cutting wheel of the mentioned tool (microtome). In addition, almost no contour was observed at a high cutting speed for a molded part made of the non-dried granules. A longer cutting time (45 min per cross-section) or in another extent slower cutting speed resulted in a much clearer visualization of the contours compared with a faster cutting (30 min per cross-section) of the part. Therefore, the color contrast was the result of the material reaction to the cutting process at some specific condition.

There should be some mechanism which changes the physical properties of the melt across the thickness direction as the initiator of the color change. An additive (such as carbon black) which is distributed nonhomogeneously (poorly mixed) had been found as a source of such variation so that flow history contours could be appeared.[9] However, in this study, no additive was used in the granules. Because the counters were only observed when injecting with non-dried granules, it could be assumed that the source of color contrast is the moisture presence. The moisture could act as an external additive which may cause a different behavior in molten plastic while flowing at various shear rates across the thickness. It must be mentioned that a deep understanding of the fountain mechanism which distributes and orients the melt in the cavity is not well presented. So, the mechanism by which the contours are made is not clear and needs further investigations.

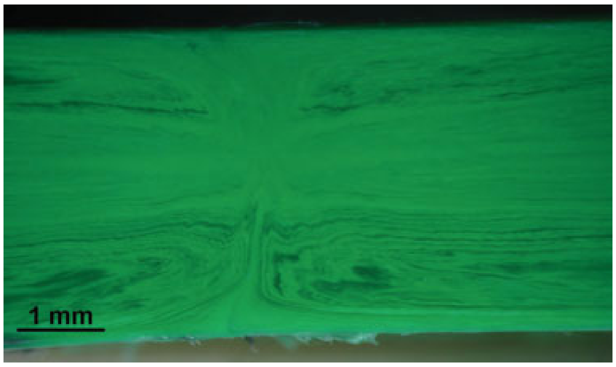

Figure 3 Micro-photography of the cross-section of the weld-line at a distance of 4 mm from the obstacle pin visualizing the flow history contours. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

As Figure 3 reveals, the merging of the two fronts (penetration) is the most at the core area of the part compared with the surface regions for the indicated distance from the pin. The difference could be attributed to the higher temperature at the core compared with the surfaces (where the lower wall temperature causes surface freezing) which in turn inhibits a more effective merging.

Image processing and quantification

Figure 4 shows the micro-photographs of the cross-sections along the weld-line in which the interface line and the penetration (direction and amount) are shown. A ''suppositional line'' is defined as the line which connects two corners of the V-notch at the two sides of the molded parts. As shown in Figure 4, this line is considered as the reference line by which the position of the interface (or the penetration depth and direction) at the cross-section is measured. It is also seen that there is a variation in the shape and length of the interface along the weld-line, which will be discussed in the following.

Figure 5 depicts the penetration depth along the weld-line versus the distance from the hole (generated by the obstacle pin). The positive/negative signs are an indicator of the relative position of penetration front to the V-notch suppositional line. Although, at the start, the penetration direction was toward the right side (according to the view point shown in Fig. 2), it then began to reverse after a maximum penetration depth of 0.58 mm [17% of the thickness (3.5 mm)] at a distance of 16 mm from the

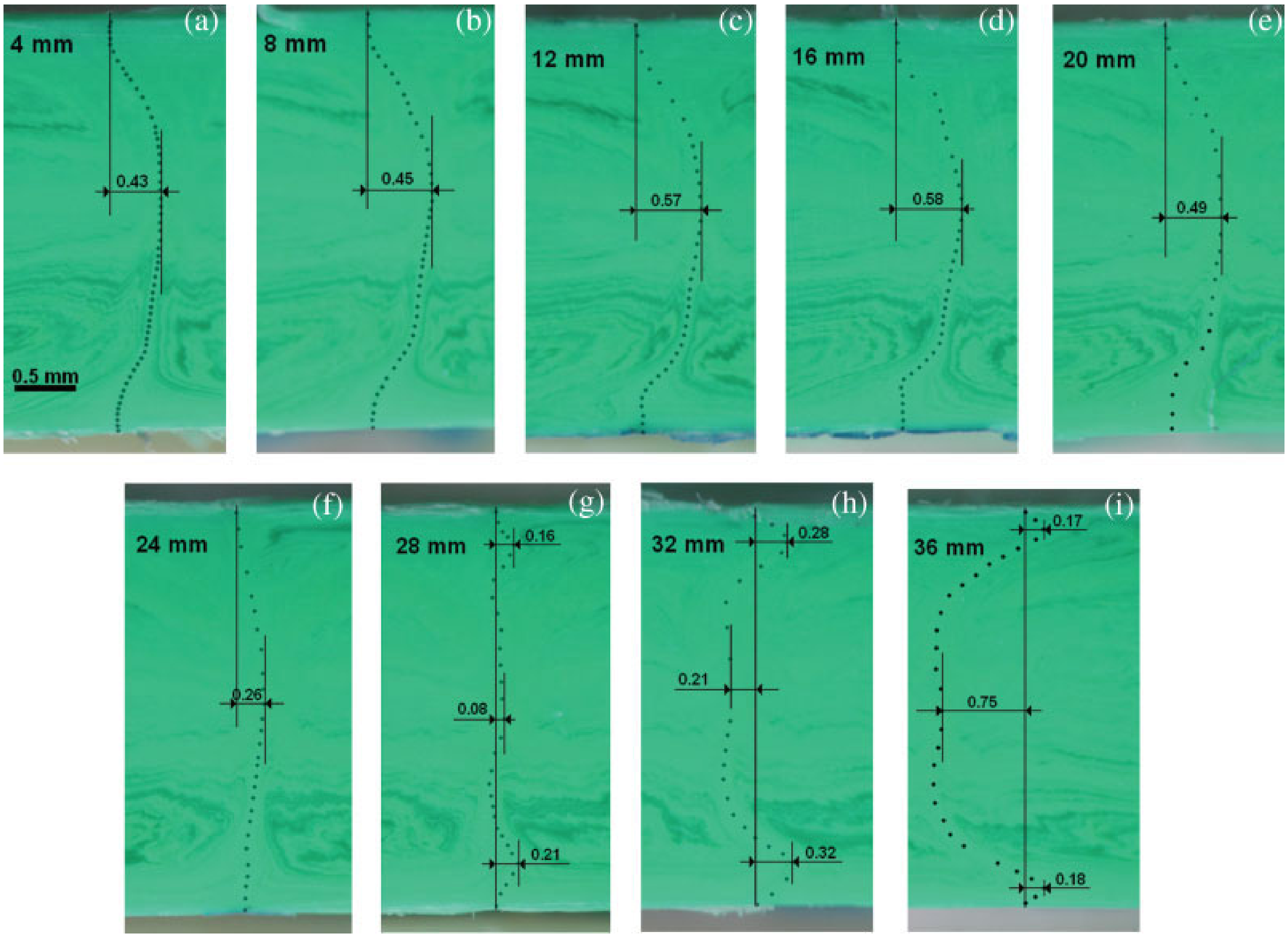

Figure 4 Penetration of one flow front to the other in weld-line cross-section at different distances from the edge of hole. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

obstacle pin. However, the interface did not reverse at the surface region which could be as a result of faster solidification associated with the cold mold wall. At a distance of almost 28 mm, it is seen that the front's interface, at the core of the part, passed the reference line. The reversed penetration continued to increase up to a depth of 0.75 mm (21% of the thickness) at a distance of 36 mm at the core of the part. It should be notified that although a deep reversed penetration is seen in the interface at the core of the part, the penetration direction is seen to remain almost unchanged at the surface layers of the part of the shown cross-sections. SEM pictures of the V-notch were prepared at various distances to measure the angle, a sample of which is shown in Figure 6. The V-notch disappeared at a distance of 16 mm behind the obstacle pin.

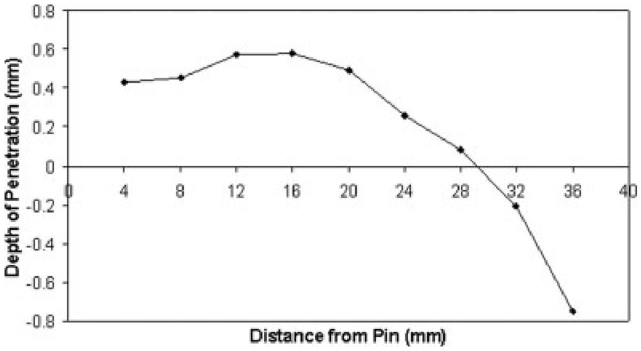

Figure 5 Variation of the penetration depth along the weld-line behind the obstacle pin.

Fronts penetration versus eccentricity

The penetration of one front to the other at the weld-line could be as a result of pressure difference of the two merging fronts when passing the obstacle pin. It means that the pressure of the penetrating side is higher than that of the penetrated one. The pressure difference could be originated from the eccentricity of the position of the obstacle pin relative to the centerline of the part, detected after exact

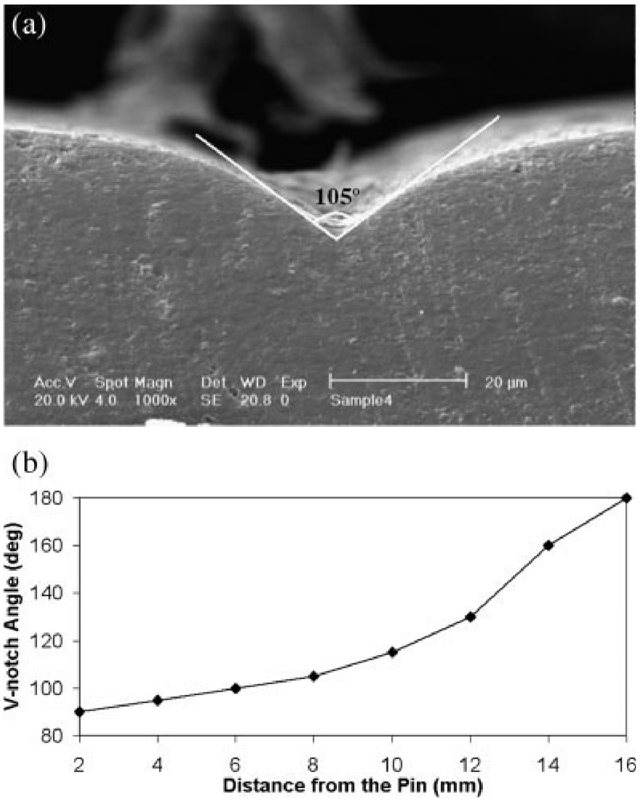

Figure 6 (a) Measuring V-notch angle using the SEM micrographs, (b) variation of the V-notch angle along the weld-line.

measuring the pin position. As shown in Figure 1, the 1.5 mm eccentricity of the position of the obstacle pin in the cavity caused a difference in the cross-section area, so that one side (A2 = 47.25 mm^2) became smaller than the other one (A1 = 57.75 mm^2).

The obstacle pin divides the cavity cross-section into two sections. When the melt passes the pin, it feels a pressure drop at both fronts. On the other hand, the smaller cross-section area results in a higher pressure drop. This difference in the cross-section area of the two sides of the pin results in a higher pressure drop of the melt passing section A2 than that of section A1. Therefore, the pressure at the front passing the larger cross-section (A1, the left side of the images in Fig. 4 according to the view direction shown in Fig. 2) will be higher than that of A2. It could be then convincing to infer that the high-pressure front (left side) tends to penetrate into the low-pressure one (right side), as observed in Figure 4 at closer distances to the hole. However, a question rises that why the penetration direction reverses at the distance further from the hole (28 mm and after); it must be noted that the penetration stops at a distance of 16 mm where it starts to reverse (the point of maximum in Fig. 5).

It could be expected that the oscillation in penetration occurs due to an oscillation of pressure at the fronts. When the high-pressure front penetrates into the low-pressure one, it somehow causes a pressure build-up at the other front (low-pressure front) by limiting its path. Thus, the fronts tend to maintain an equilibrium position toward the centerline which could cause interface oscillation. One could also speculate that the difference in pressure drops will be smaller further along the weld-line, which in turn, promotes the reverse of the penetration direction.

It is interesting to note that the elimination of the V-notch was observed to occur at the same distance of 16 mm (Fig. 5—point of maximum) where the interface penetration direction starts to reverse (Fig. 4). This could suggest a correlation between material behavior at the core and the surface of the part. The correlation introduces an area which is highly affected by the obstacle pin (obstruction affected zone) broadened in a distance not exceeding the obstacle diameter; it is in agreement with the earlier studies.[3,4,8]

CONCLUSIONS

A quantitative visualization study on the cross-section of a weld-line originated by an obstacle pin was carried out. The flow contours of the molded part along the weld-line at the interface of the two adjacent flows were visualized using a novel technique. The visualized flow history contours revealed the interface of the two adjacent flows by which a penetration of one flow front to the other at the interface was recognized and an oscillation in the direction of the penetration was observed along the weld-line. The interface oscillation was correlated to an eccentricity in the position of the obstacle pin. SEM micrographs were also captured to characterize the V-notch along the weld-line at the surface of the molded part, to investigate a correlation between internal and external behavior of the molten plastic along the thickness direction during weld-line formation. The results could yield the following conclusions:

- Quantitative visualization of the flow history contours at the cross-section of a weld-line could be a useful means to investigate the material behavior at the interface.
- A penetration of one front to the other of two adjacent flows can be revealed through the applied visualization. The penetration was inferred to be originated by an eccentricity in the position of the obstacle pin.
- An oscillation in the direction of the penetration was revealed via sequencing the visualized flow history contours along the weld-line.

- A correlation in material behavior between the surface and core of the molded part was investigated along the weld-line. The correlation suggests an area affected by the presence of the obstruction (obstacle) to be called (OAZ) found to be less than the obstacle diameter.

References

1. Nguyen-Chung, T. Rheol Acta 2004, 43, 240.
2. Yamada, K.; Tomari, K.; Harada, T.; Hamada, H. SPE ANTEC: San Francisco, CA, 2002.
3. Yamada, K.; Tomari, K.; Harada, T.; Hamada, H. SPE ANTEC: Nashville, TN, 2003.
4. Yamada, K.; Tomari, K.; Harada, T.; Hamada, H. SPE ANTEC: Chicago, IL, 2004.
5. Kim, S. G.; Suh, N. P. Polym Eng Sci 1986, 26, 1200.
6. Fellahi, S.; Meddad, A.; Fisa, B.; Favis, B. D. Adv Polym Technol 1995, 14, 169.
7. Tomari, K.; Tonogai, S.; Harada, T.; Hamada, H.; Lee, K.; Morii, T.; Maekawa, Z. Polym Eng Sci 1990, 30, 931.
8. Nguyen-Chung, T.; Mennig, G.; Boyanova, M.; Fakirov, S.; Balta Calleja, F. J. J Appl Polym Sci 2004, 92, 3362.
9. Swyer, L. C.; Grubb, D. T. Polymer Microscopy; Chapman and Hall: London, 1987; Chapter 5.