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ORIGINAL ARTICLE

Mold surface roughness effects on cavity filling of polymer melt in micro injection molding

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Abstract Micro injection molding presents many challenges in the injection-molding community. When the dimensions of the part (and thus the cavity of the mold) are small, micro-scale factors such as mold surface roughness may play an important role in the filling of polymer melt. This paper investigates the effects of mold surface roughness on cavity filling of polymer melt in micro injection molding. A disk insert, which has two halves with different surface roughness but with the same roughness mean lines, was used in the investigations. The ratio of flow area of the rougher half with the total flow area of the molded part is used to evaluate the significance of surface roughness effect. The experimental results revealed that mold surface roughness does resist the cavity filling of polymer melt in micro injection molding. For the limited range of injection rate investigated, it is not significant on the surface roughness effects. The increase of mold temperature will decrease surface roughness effects. The change of melt temperature within the range allowed by the process is insignificant for surface roughness effects.

Keywords Micro injection molding · Surface roughness · Polymer filling

1 Introduction

Micro injection molding is a major process for cost-effective mass production of micro plastic parts. Extensive investigations of micro injection molding have been carried out on the optimization of the process parameters [1–4]. However, there are only a few investigations on the effects of mold surface roughness. When the dimensions of a part (and thus the cavity of the mold) are small, mold surface roughness may play an important role in the flow of polymer melt [5]. As the mold surface roughness increases, the contact area between the polymer melt and the mold wall will also increase. Heat transfer between the melt and the wall is enhanced as the heat transfer rate is proportional to the contact surface area [6]. Smialek and Simpson [7] found that an increase of mold surface roughness can prevent slippage during filling and lead to a more appealing surface of the molded parts. Griffiths et al. [8] investigated the flow behavior of polymer melt in micro cavities with different surface roughness levels through experiment and Taguchi technique. Polypropylene (PP), acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) were used and the experimental results showed that mold surface roughness has an influence in the level of turbulence in the melt flow, but its effect on the slip-stick phenomena was not identified. Theilade et al. [6] performed experiment to study the effects of mold surface roughness on linear part shrinkage through injection molding of polystyrene (PS) and polypropylene (PP). A two-cavity tool, with each cavity having different surface topographies, was used. The experimental results showed that a rough surface yields a lower linear shrinkage for either PP or PS.

Previous research conducted on fluid flow in micro channels, conduits and tubes [5, 9–14] indicates that surface roughness may have significant effects on pressure gradient, friction factor and heat transfer. However, the fluids used in these investigations were assumed to be Newtonian and in steady state. These assumptions are not applicable to micro injection molding.

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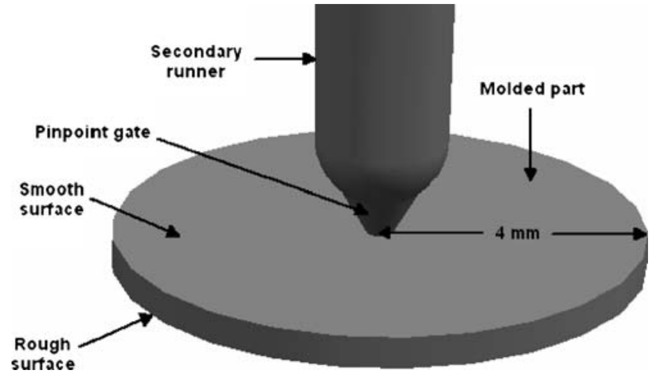

Fig. 1 Design of the molded part with dimensions

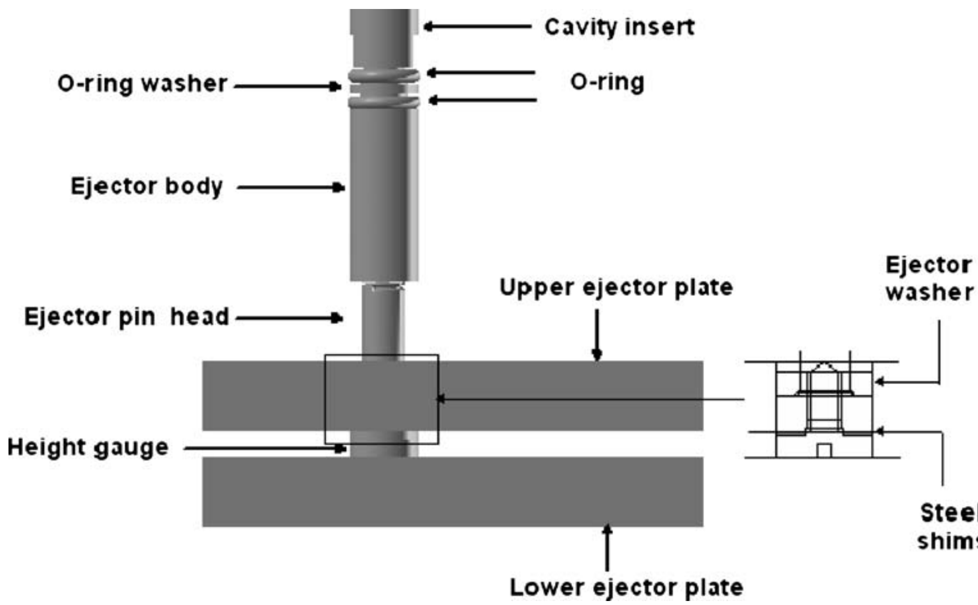

Fig. 2 Installation of the cavity insert

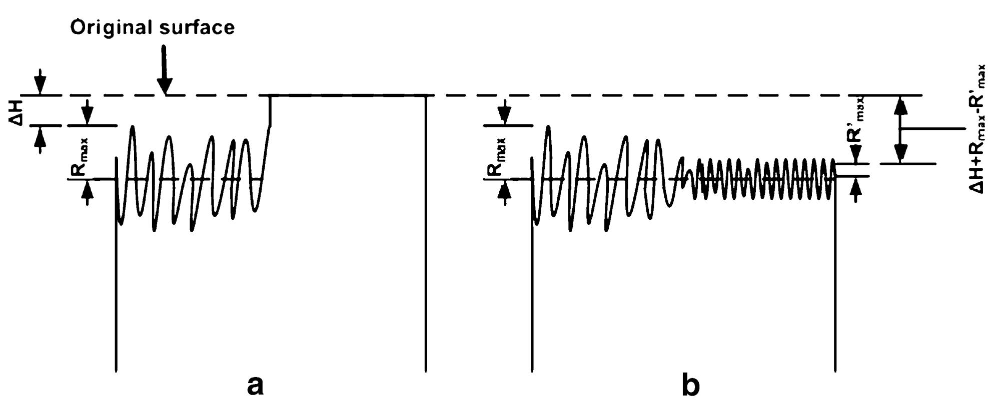

Fig. 3 EDM machining of the cavity insert: **a** First half; **b** Second half

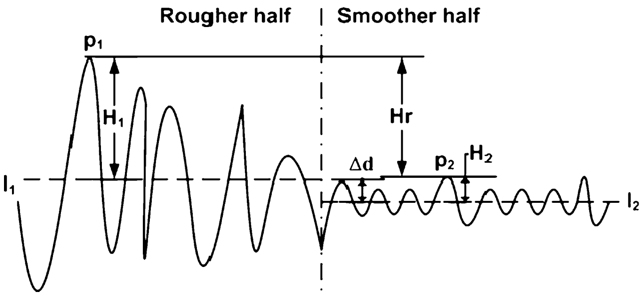

Fig. 4 The method to determine the difference of the mean lines between the two halves

This paper investigates the effects of mold surface roughness on the cavity filling of polymer melt (i.e., polyoxymethylene) at different injection rates with different mold and melt temperature. A disk insert, which has two halves with different surface roughness but with the same roughness mean lines, was used. The two halves with different roughness were machined on the bottom wall of the mold cavity. The ratio of flow area of the rougher half with the total flow area of the molded part is used to evaluate the significance of surface roughness effects.

2 Experimental design

Figure 1 shows the design of the molded part. The upper wall of the mold cavity is provided by a moving plate and is very smooth. The lower wall is provided by a cavity insert. The two halves of the cavity insert have different surface roughness but with the same mean lines such that the two halves of the mold cavity have the same volume. This is to ensure that the filling of the two halves of the mold cavity were under the same processing conditions, e.g., injection pressure, injection rate, mold temperature (i.e., T_{mold}) and melt temperature (i.e., T_{melt}). Therefore, mold surface

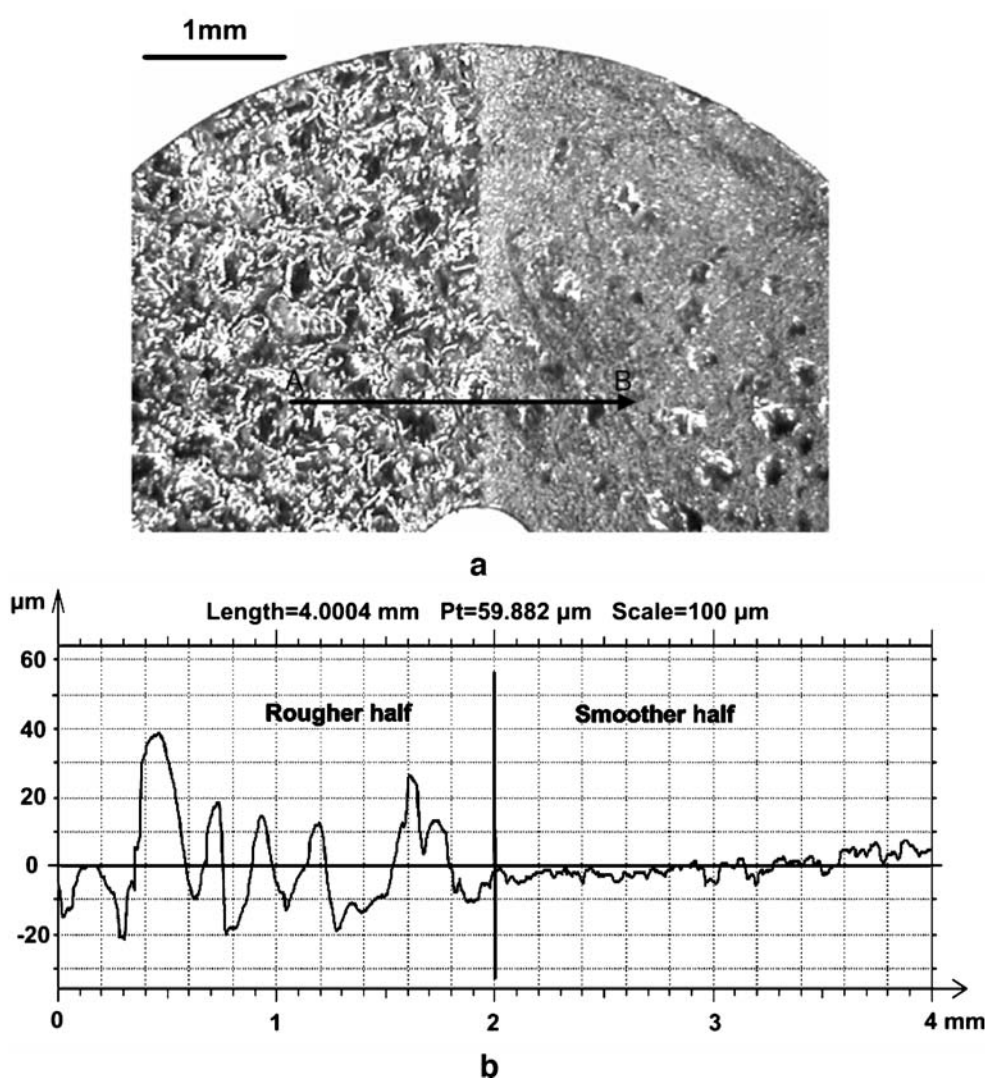

Fig. 5 Surface feature of the cavity insert machined using EDM

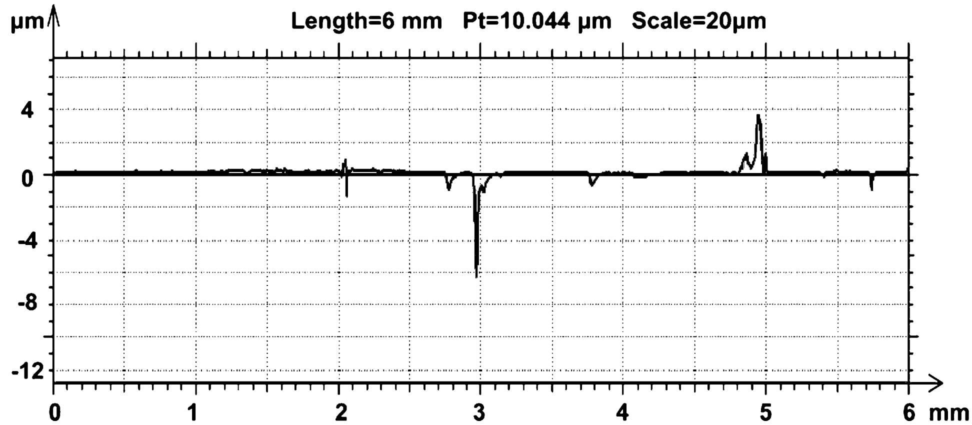

Fig. 6 Measured roughness profile of the upper wall of the mold cavity

roughness effect can be investigated by comparing the difference in flow area between the two halves of the molded part. Moreover, the separating line between the two halves of the mold insert was adjusted vertically in order that the gravity has the same effect on the filling of the two halves of the cavity.

The cavity insert was mounted onto an ejector pin. Figure 2 shows the installation of the cavity insert. The mold cavity thickness was controlled using the same method as described in [4], i.e., thin stainless-steel shims were placed in between the height gauge and the ejector pin head in order to control the thickness of the cavity, while the thickness of the ejector washer was reduced to accommodate the dimensional increase.

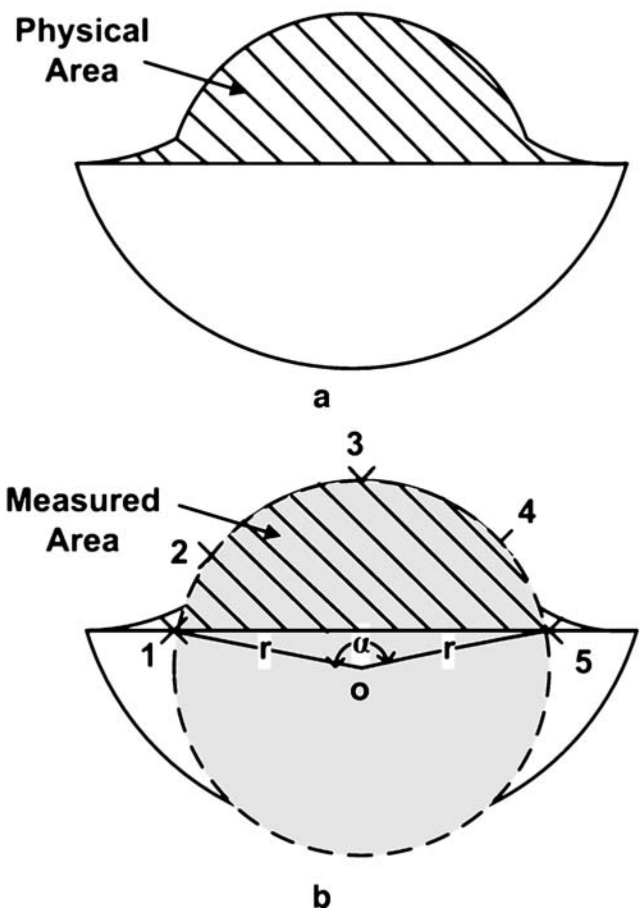

Fig. 7 Procedure for determination of flow area of the small half of molded parts: **a** Physical area to be determined. **b** Calculated area

3 Machining of cavity inserts

To machine the two halves of the cavity with different roughness but the same mean lines, an electronic-discharge-machine (EDM) was used. One half is first machined using a specific cut depth (i.e., ΔH) and a high surface roughness level identified by the expected R_{max} and R_a. Subsequently, the second half is machined using a low roughness level identified by the expected R'_{max} and R'_a, and the cut depth of ($\Delta H + R_{max} - R'_{max}$). The surface profile of the cavity insert is then measured using a Talyscan 150 dual gauge system to ensure that the mean lines of the two halves are at the same level. If not, the process is repeated until the mean lines of both halves are almost at the same level. Figure 3 illustrates the procedure of machining the surface of the cavity insert. Figure 4 shows the method to determine the difference of the mean lines between the two halves based on the measured surface profile. The distance from the mean line of the rougher half (i.e., l_1) to that of the smoother half (i.e., l_2) can be expressed as

$$\Delta d = H_r - (H_1 - H_2) \quad (1)$$

where H_1 is the distance from point P_1 to the mean line of the rougher half (i.e., l_1), H_2 is the distance from point P_2 to the mean line of the smoother half (i.e., l_2), and H_r is the vertical distance from point P_1 to point P_2. Thus, $\Delta d=0$ means the mean lines of the two halves are at the same level, $\Delta d>0$ means the mean line of the rougher half is higher than that of the smoother half, and $\Delta d<0$ means that mean line of the rougher half is lower than that of the smoother half.

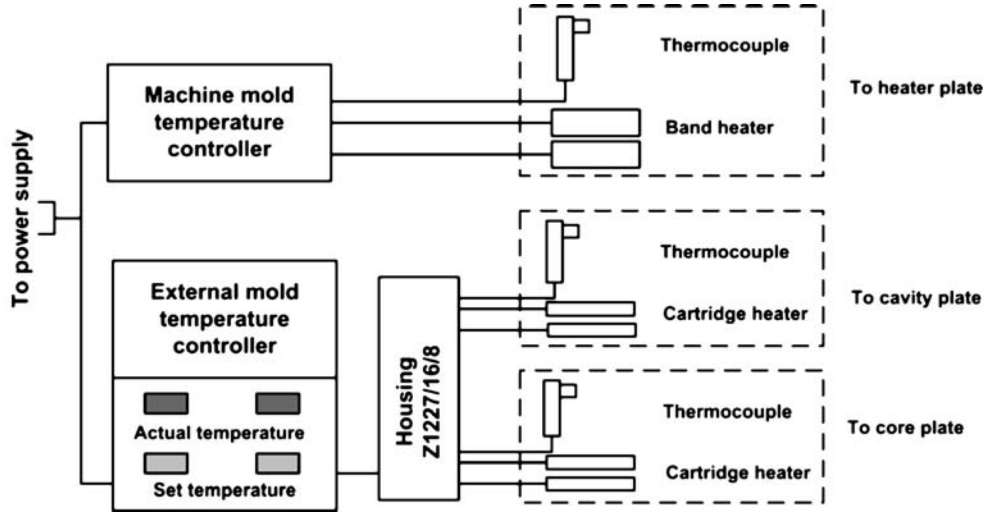

Fig. 8 Schematic diagram on connection of temperature control system

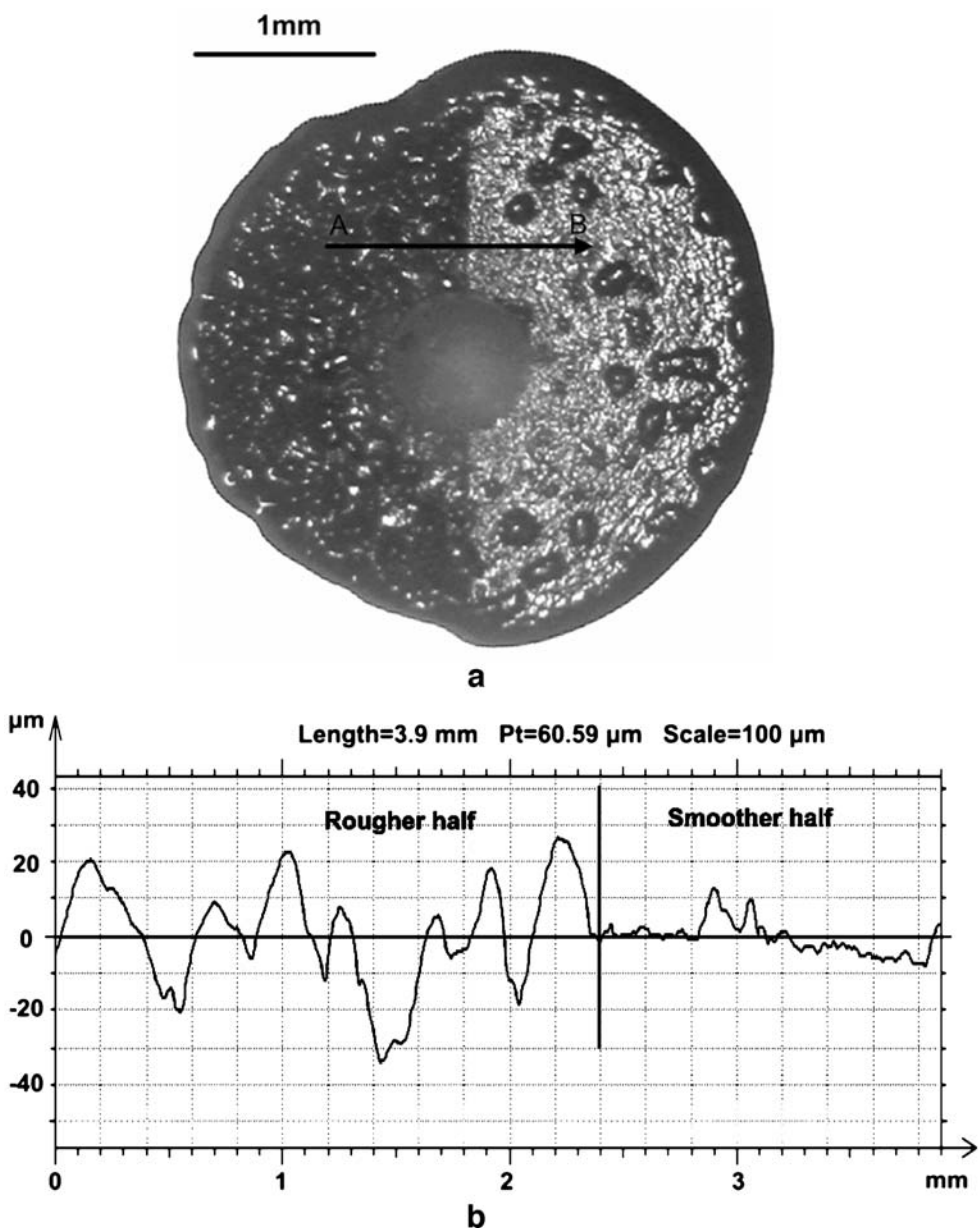

Fig. 9 A molded part: **a** microscopic image; **b** Roughness profile measured in the A–B direction

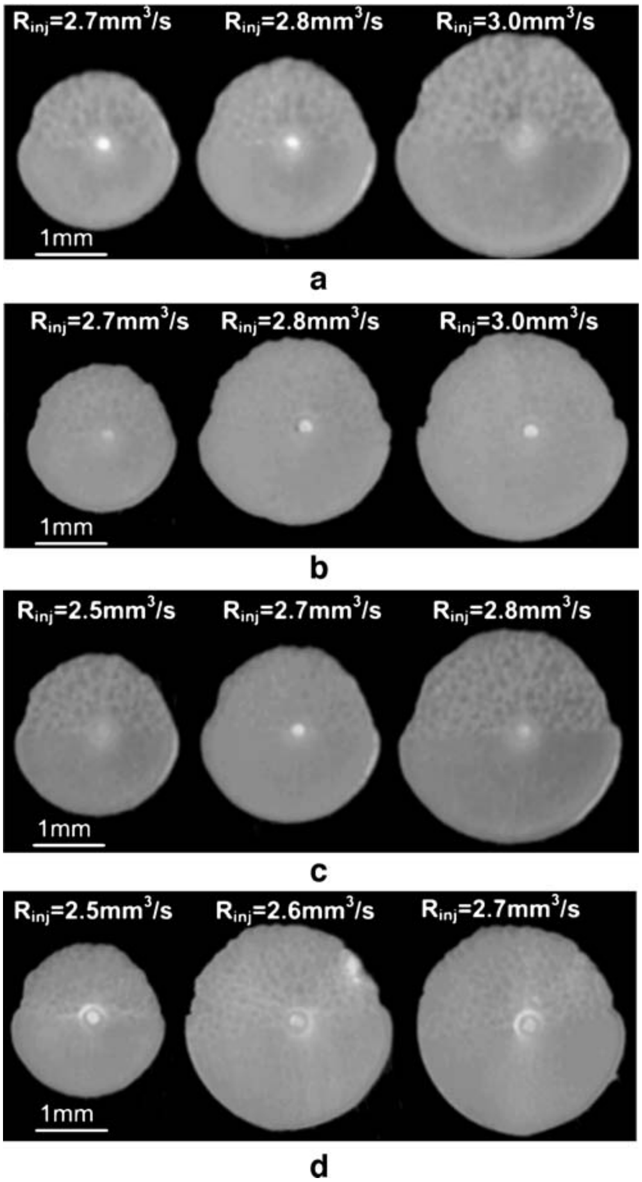

Fig. 10 Images of molded parts of different sizes at different injection rates with: **a** T_{melt}=453 K and T_{mold}=323 K. **b** T_{melt}=453 K and T_{mold}=383 K. **c** T_{melt}=473 K and T_{mold}=323 K. **d** T_{melt}=473 K and T_{mold}=383 K

Figure 5 shows a microscopic image of the surface of the machined cavity insert and its roughness profile measured along the A-B direction. It can be observed that although the two halves are of different surface roughness (i.e., the rougher half has Ra of 5.1 μm, and the smoother half has Ra of 1.6 μm) they have almost the same mean lines. Based on the measurement, the mean line of the rougher half is 1 μm higher than that of the smoother half, which was not taken into consideration in the experimental analysis.

Figure 6 shows the measured roughness profile of the upper wall of the mold cavity. It can be observed that the upper wall is very smooth (i.e., Ra=0.037 μm) and its surface roughness can be neglected as compared to the lower wall.

4 Determination of flow area

Mold surface roughness effect is investigated through the analysis of the difference of flow area between the two halves of the molded part. Therefore, it is very important to determine the flow area of the two halves accurately. However, the shape of the molded part is usually not very regular, and the flow area of the molded part is not easy to obtain from direct measurement. Figure 7a shows a typical pattern of the molded part. Using a ROI OMIS II series optical microscope, the flow area of the smaller half is determined with the following procedure:

1. Five points are selected, evenly distributed along the edge of the smaller half. Two of the points must be located on the separator line, e.g., the points 1 and 5 as shown in Fig. 7b.
2. A fitted circle is generated using the five points, and the center point of the circle, o, and the radius, r, are obtained.
3. Two lines are drawn from the center, o, to point 1 and 2.
4. The angle between the two lines, α is obtained.
5. The area of the small half is calculated using

$$\text{Area} = \pi r^2 \frac{\alpha}{360} - r^2 \cos\frac{\alpha}{2} \sin\frac{\alpha}{2} \tag{2}$$

Similarly, the area of the larger half can be obtained. The total area of the molded part is the sum of area of the two halves.

5 Experimental procedure

In the experiment, the height of the mold cavity is adjusted to 250 μm. The material used is polyoxymethylene (POM), Ultraform W2320 003. Four cartridge heaters were used to heat up the micro mold and the mold temperature was monitored using two thermocouples. Figure 8 shows the schematic diagram on connection of the temperature control system. Partially filled parts of different sizes were obtained by varying the injection rates ranging from 2.5 to 3.0 mm^3/s. Mold temperature and melt temperature were varied to investigate their significance for the surface roughness investigated. For every change in the parameter setting, five specimens were collected only after 10 cycles of the injection process. This was to stabilize the parameter setting and to obtain consistent plastic parts.

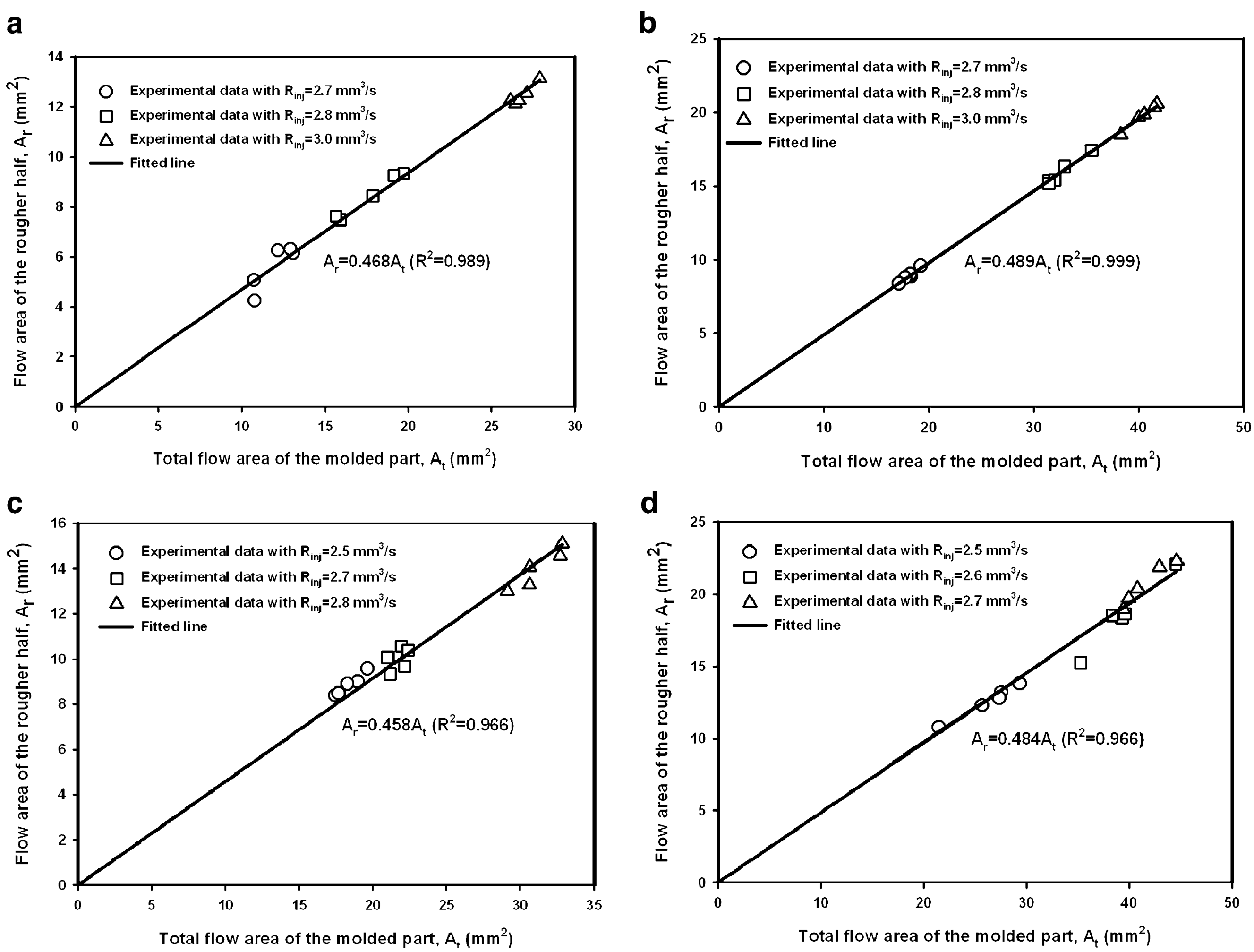

Fig. 11 Fitted lines for the measured data with: **a** T_{melt}=453 K and T_{mold}=323 K. **b** T_{melt}=453 K and T_{mold}=383 K. **c** T_{melt}=473 K and T_{mold}=323 K. **d** T_{melt}=473 K and T_{mold}=383 K

6 Results and discussion

Figure 9a shows a microscopic image of a molded part that is molded with injection rate of 2.7 mm^3/s, mold temperature of 323 K and melt temperature of 453 K. It can be observed that the rougher half of the cavity insert results in higher surface roughness of the molded part, and smoother half results in lower surface roughness of the molded part. Figure 9b shows the measured roughness profile of the molded part along the A-B direction. It gives a value of Ra=4.4 μm and Ra=1.4 μm for the rougher and smoother halves respectively. Comparing with the value of Ra=5.1 μm and Ra=1.6 μm for the rougher and smoother halves of the cavity insert, the molded part has good replication of mold surface roughness.

Figure 10a–d show the molded parts of different sizes at different injection rates with different mold and melt temperature levels. It can be observed that the flow area of the rougher half is smaller than that of the smoother half. This indicates that the rougher the surface, the more the resistance to the flow of the polymer melt during cavity filling.

To investigate the significance of injection rate, melt temperature and mold temperature for the surface roughness investigated, an impact factor, i.e., the ratio of flow area of the rougher half with the flow area of the whole molded part, is defined. The ratio is determined from the slope of the line obtained through curve-fitting the experimental data using the linear function:

$$A_r = kA_t \quad (3)$$

where, A_r stands for flow area of the rougher half, A_t stands for total flow area of the molded part, and k is the ratio. The value of k is bounded between 0 and 1. There will be negligible roughness effect if k=0.5, indicating that there is similar flow area for both halves with different roughness. The larger the difference in the value of k from 0.5, the more significant is the roughness effect. As the ratio, k, is defined using the rougher half, it is expected that the value of k is less than 0.5.

Figure 11a–d shows the fitted lines with the coefficients of determination (R^2) for the experimental data at different injection rates with different mold temperature and melt temperature. It can be observed that although the short shot obtained with a larger injection rate will result in larger flow area, it will not result in significant difference in the value of k (i.e., the roughness effect) as the experimental data at different injection rates are close to the fitted line.

From Fig. 11a–b, when the melt temperature is kept constant at 453 K and the mold temperature is increased from 323 to 383 K, the value of k increases from 0.469 to 0.489, namely, an increase of 4.5%. From Fig. 11c–d, when the melt temperate is kept constant at 473 K and the mold temperature is increased from 323 to 383 K, the value of k increases from 0.458 to 0.484, namely, an increase of 5.7%. It can be observed that the value of k is significantly dependent on the mold temperature used in the experiment. When the melt temperature is kept constant, an increase in the mold temperature will decrease the effects of surface roughness.

From Fig. 11a and c, when the mold temperature is kept constant at 323 K, an increase in the melt temperature from 453 to 473 K decreases the value of k from 0.468 to 0.458, namely, a decrease of 2.1%. From Fig. 11b and d, when the mold temperature is kept constant at 383 K, an increase in melt temperature from 453 to 473 K will decrease the value of k from 0.489 to 0.484, namely, a decrease of 1.0%. It can be observed that the change of melt temperature within the range allowed by the process has no significant effect on the value of k. Furthermore, considering the fact that the quality of the linear fit in Fig. 11c and d is not high enough (i.e., R^2=0.963 and 0.9644, respectively) as compared to that in Fig. 11a and b (i.e., R^2=0.988 and 0.999, respectively). The values of k obtained in Fig. 11c and d have larger fitting errors. Therefore, it is not safe to state that an increase in melt temperature will increase the effects of surface roughness when the mold temperature is kept constant. To clarify the effect of the melt temperature, further experiments using different cavity inserts should be performed from a statistical point of view.

7 Conclusions

Mold surface roughness effects on the cavity filling of polymer melt were investigated experimentally. With the same process parameters, the mold cavity that has a higher surface roughness will result in a smaller molded part with higher surface roughness. This is due to the higher resistance to the flow of polymer melt during cavity filling. For the limited range of injection rate investigated, it is not significant on the surface roughness effects. When the melt temperature is kept constant, an increase in mold temperature will decrease the effects of surface roughness. When the mold temperature is kept constant, the change of melt temperature within the range allowed by the process is not significant for the surface roughness effect.

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References

1. Yu LY, Koh CG, Lee LJ, Koelling DW (2002) Experimental investigation and numerical simulation of injection molding with micro-features. Int Comm Heat Mass Transfer 42(5):871–888
2. Zhao J, Mayes RH, Chen G, Xie H, Chan PS (2003) Effects of process parameters on the micro molding process. Polymer Eng Sci 43(9):1542–1554
3. Shen YK, Wu WY (2002) An analysis of the three-dimensional micro-injection molding. Int Comm Heat Mass Transfer 29 (3):423–431
4. Ong NS, Koh YH (2005) Experimental investigation into micro injection molding of plastic parts. Mater Manuf Process 20:1–9
5. Kleinstreuer C, Koo J (2004) Computational analysis of wall roughness effects for liquid flow in micro-conduits. J Fluids Eng 126:1–9
6. Theilade UR, Kjaer EM, Hansen HN (2003) The effect of mold surface topography on plastic part in-process shrinkage in injection molding. ANTEC 1:463–467
7. Smialek CD, Simpson CL (1998) Flow instabilities in thin-wall injection molding of thermoplastic polyurethane. ANTEC 3:3373–3377
8. Griffiths CA, Dimov SS, Pham DT (2006) Micro injection moulding: the effects of tool surface finish on melt flow behaviour. Multi Mater Micro Manuf Proc, Elsevier, Amsterdam, pp 1–4
9. Croce G, Agaro PD (2004) Numerical analysis of roughness effect on microtube heat transfer. Supperlattice Microst 35:601–616
10. Koo J, Kleinstreuer C (2003) Liquid flow in microchannels: experimental observations and computational analysis of microfluidics effects. J Micromech Microeng 13:568–579
11. Koo J, Kleinstreuer C (2005) Analysis of surface roughness effects on heat transfer in micro-conduits. Int J Heat Mass Transfer 48:2625–2634
12. Hu YD, Werner C, Li DQ (2003) Influence of three-dimensional roughness on pressure-driven flow through microchannels. J Fluids Eng 125:871–879
13. Qu WL, Mala GH, Li DQ (2000) Heat transfer for water flow in trapezoidal silicon microchannels. Int J Heat Mass Transfer 43:3925–3936
14. Mala GM, Li D (1999) Flow characteristics of water in microtubes. Int J Heat Fluid Flow 20(2):142–148