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ORIGINAL ARTICLE

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Injection molding of polymer micro- and sub-micron structures with high-aspect ratios

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Abstract This work studies the injection molding characteristics of polymer micro- and sub-micron structures using demonstration mold inserts with micro- and sub-micron channels with high-aspect ratios. The effects of the injection molding parameters on the achievable aspect ratio of the micro- and sub-micron walls were investigated. Additionally, distinctive mold-filling behaviors and resulting defects were observed for various polymers, such as polymethyl methacrylate (PMMA), polypropylene (PP) and high-density polyethylene (HDPE). Experimental results reveal that the mold temperature determines the success of the injection molding of micro- and sub-micron walls. The satisfactory mold temperature for micro-injection molding significantly exceeds that for traditional injection molding. Moreover, the main injection pressure and the main injection time substantially affect the achievable aspect ratio of the micro- and sub-micron walls. Furthermore, unusual flow behaviors occur and poor molding results are obtained when PP and HDPE are used for micro-injection molding.

Keywords High-aspect ratio · Injection molding · Micro-structures · Molding characteristics · Sub-micron structures

1 Introduction

Micro- and sub-micron structured components have many potential applications. These components most commonly are made of polymers, so technology for manufacturing polymer micro- and sub-micron structures is very important [1, 2]. The economical fabrication of high quality polymer micro- and sub-micro-structures is a challenge that must be met as micro- and sub-micron structured components become more widely used [3, 4]. The injection molding process is anticipated to hold great potential in the mass production of uniform, good quality polymer micro- and sub-micron structures [5]. However, satisfactory molding results of polymer micro- and sub-micron structures whose aspect ratios exceed two are hard to obtain with the existing injection molding equipment and techniques for polymers [6, 7] for various reasons [8]. The most basic reason is that micro-cavities made on the surface of the mold insert for fabricating polymer micro-structures are much more narrow than the cavity of common injection molds. This not only increases the filling resistance of the molding polymer, but also promotes the cooling effect of the mold on the molding polymer. Therefore, the filling of the micro-cavities and the power consumption of the injection molding machine are highly sensitive to variations in mold temperature and the injection pressure in the micro-injection molding process [4]. The homogeneity of micro-molding polymers is also an important consideration [9]. Accordingly, whether the development of morphology (crystal and phase) in the polymer affects the injection molding characteristics of the micro- and sub-micron structures should be addressed.

In this study, injection molding experiments are conducted on polymer micro- and sub-micron structures, using demonstration mold inserts with micro- and sub-micron channels with high-aspect ratios. The aim is to determine the parameters that dominate the success of micro-injection molding. The effects of the variations of these parameters on the achievable aspect ratio value of the molded micro- and sub-micron structures are investigated. The filling behaviors of the molding material in the micro-mold cavities are also identified.

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2 Micro-injection molding experiments

Demonstration mold inserts whose surfaces have micro- and sub-micron channels with high-aspect ratios are used to perform injection molding experiments. The objective here is to examine the moldablity and the and the molding characteristics of polymer micro- and sub-micron structures. All mold inserts are fabricated from 8-mm square silicon wafers. Anisotropic wet etching and (110) silicon wafers are used to fabricate the mold inserts with surface micro-channels that are wider than 1 μm, with widths of 20, 10 and 2 μm, and aspect ratios of over 12 [10–13]. E-beam lithography and (100) silicon wafers are used to fabricate the other mold inserts whose surface sub-micron channels have aspect ratios of about six. The fabricated mold insert is fixed by continuous sucking on the top end plane of the ejector pin, which is machined to have a suction hole along the pin axis, in the mold. The thickness of the mold cavity corresponding to the base of the molding micro-structures product is 2.5 mm. During the injection molding cycle, the whole mold cavity and the runner system are continuously vacuumed to keep the pressure less than 1 mbar before they are filled with the molding material. The mold temperature is strictly controlled using a temperature-controlled cyclic-water system and electric heaters that are built into the mold.

Amorphous polymer polymethyl methacrylate (PMMA) and crystalline polymers, polypropylene (PP) and high density polyethylene (HDPE), are the experimental materials. Each is baked at an appropriate temperature for six hours to remove the moisture just before it is used in injection molding. In this work, the setting injection pressure in the mold filling stage of an injection molding cycle is stepped in two stages: the first value of the injection pressure is to fill the part of the mold cavity that corresponds to the base of the molding micro-structures produced; and the second injection pressure, called the "main injection pressure", is for filling the micro-mold cavities (micro-channels). The pressure of the molding material in the mold cavity and the temperature of the cavity wall are measured using a pressure sensor and a thermal couple, respectively, which are embedded in the cavity wall opposite the mold insert. After it has been packed and cooled, the molded working part is ejected from the mold, together with the mold insert. A ARBURG-270S injection molding machine was used. Then, KOH is used to etch off the silicon mold insert, which is used as a sacrificial mold. Finally, the injection-molded micro- and sub-micron structure products are split by cooling with liquid nitrogen and observed by scanning electron microscopy (SEM).

3 Effects of injection molding parameters on the moldablity of polymer micro- and sub-micron structures

In micro-injection molding, the thickness of micro-channels or the sub-micron channels on the surface of the mold insert is approximately three orders of magnitude smaller than that of the mold cavity for common products. For polymer filling into a cavity channel of thickness h with velocity v_{av}, the mean shear strain rate of the polymer is:

$$\dot{\gamma}_{av} = v_{av} / (h/2) \quad (1)$$

and its shear stress, which is the deformation resistance, can be expressed as:

$$\tau = \eta \dot{\gamma} \quad (2)$$

where η is the viscosity of the polymer, and is a function of temperature. These equations reveal that the mean shear strain rate of the polymer in the micro-injection molding is thousands of times of that in common injection molding, to achieve the same filling velocity of the polymer. Additionally, the filling resistance of the polymer in micro-injection molding is markedly higher. Hence, more power must be provided by the injection molding machine to ensure successful micro-injection molding. However, the deformation resistance of the polymer injected into the micro cavity must be reduced to perform micro-injection molding at limited machine power. One of the most direct methods is to keep the filling polymer at a high temperature to obtain a relatively low viscosity of the polymer, by increasing the barrel temperature of the injection molding machine and the mold temperature. The latter, which more rapidly and strongly affects the temperature of the polymer injected into narrow-cavity molds, is particularly important in micro-injection molding. In fact, to fill the micro- and sub-micron channels successfully, the mold temperature must normally be greater than the glass transition temperature (T_g) of the polymer used. Figure 1 presents the results of micro-injection molding at two mold temperatures. The achievable aspect ratio value of the PMMA micro-walls that protrude from the base with a wall-thickness of 25 μm is barely one at a mold temperature of 92 °C (which is 10 °C lower than the T_g of PMMA), even if the main injection pressure applied exceeds 140 MPa, as shown in Fig. 1a. However, thinner micro-walls with a thickness of 20 μm and an aspect ratio of six can be molded perfectly at a lower main injection pressures as the mold temperature is increased to 120 °C, as shown in Fig. 1b. This fact demonstrates that the mold temperature greatly influences the moldablity of micro-structures. However, an excessively high mold temperature will have some negative consequences. Figure 2 displays an SEM micrograph of a cross-section of the micro-walls injection molded at a mold temperature of 160 °C. Residual cavities can be observed inside the micro-walls and at their base, in places causing localized bulges. Evidently, these cavities, except for the vacuum cavities generated by the shrinkage of the polymer, are formed by the remainder of the gas at high pressure. The residual gas can be regarded as being generated by the gasification of some of the molding polymer, because the polymer used was completely dried just before the experiment had begun and the air in the mold cavity was evacuated continuously during the injection molding process. The gasification of the molding polymer is caused by an excessive increase in the temperature of the polymer. The excessive increase in the polymer temperature is explained by the poor emission of the extra heat that is generated by the severe shearing of the molding polymer flowing through the gate, because the mold temperature is too high. Furthermore, the packing operation as the mold is being cooled causes the pressure of the remaining gas to be high. Therefore, after the mold insert has been removed, the compressed gas expands and deforms the micro-walls. In this work, all the cases of micro-injection molding at mold temperatures of 160 °C or above exhibited the phenomenon in Fig. 2. The phenomenon is more serious at higher mold temperatures.

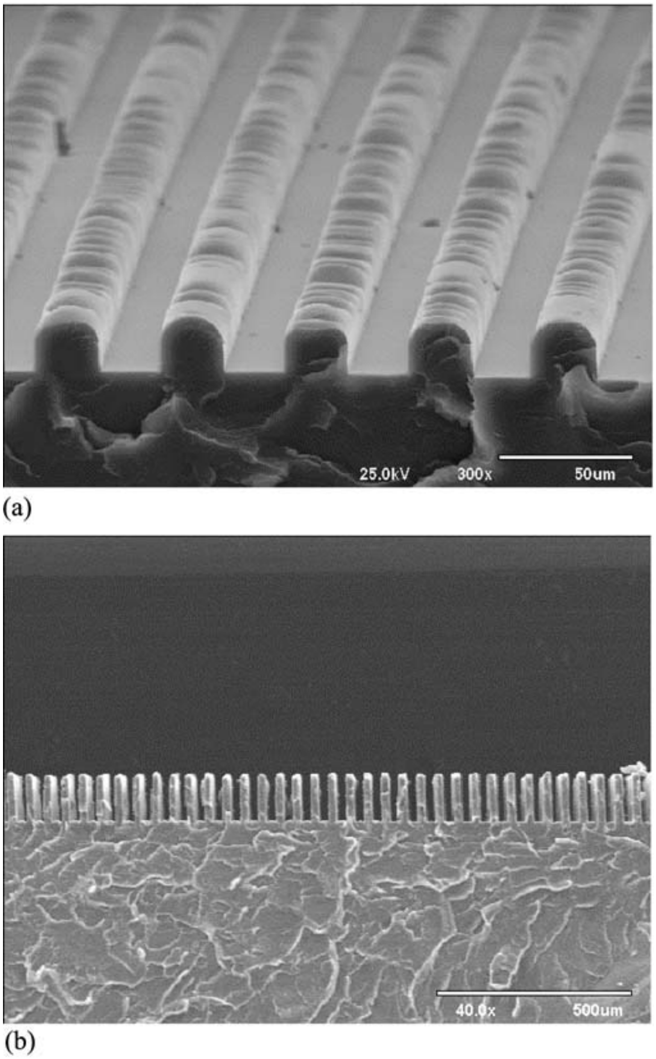


Fig. 1a,b. SEM micrographs of injection molded PMMA micro-walls (molded at a barrel temperature of 250 °C) **a** Wall thickness 25 μm (molded at a mold temperature of 92 °C, and a main injection pressure of 140 MPa for 30 s) **b** Wall thickness 20 μm (molded at a mold temperature of 120 °C, and a main injection pressure of 90 MPa for 30 s)

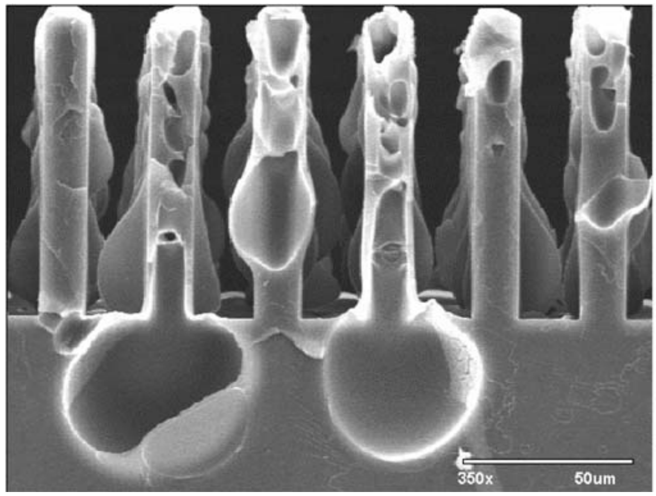


Fig. 2. SEM micrograph of a PMMA micro-walls part injection molded at an excessively high mold temperature of 160 °C (molded at a barrel temperature 250 °C, and a main injection pressure of 120 MPa for 30 s)

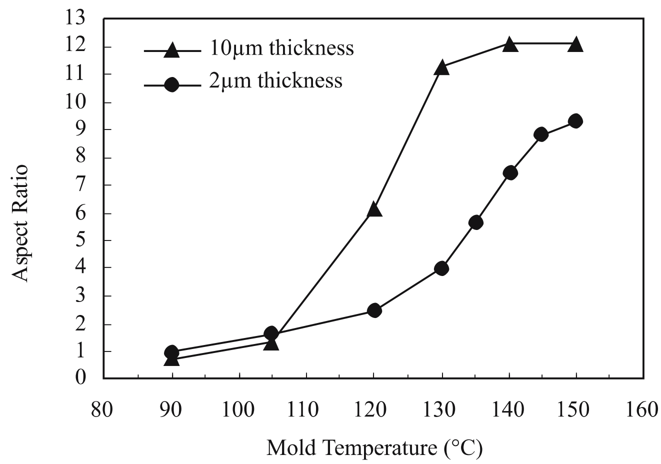


Fig. 3. Effects of mold temperature on the achievable aspect ratio of the micro-walls (molded at a barrel temperature of 250 °C, and a main injection pressure of 120 MPa for 30 s)

Figure 3 shows the effects of mold temperature on the achievable aspect ratio of the micro-walls. For micro-walls with a wall-thickness of 10 μm, the achievable aspect ratio increases substantially with mold temperature between 105 °C and 130 °C. When the mold temperature exceeds 130 °C, the rate of increase of the achievable aspect ratio of the micro-walls declines and the achievable aspect ratio tends towards a constant of about 12. For micro-walls that are thinner than 2 μm, however, the achievable aspect ratio rapidly increases with mold temperatures between 120 °C and 145 °C. This temperature range is 15 °C above that at of 10-μm thick micro-walls, and demonstrates a rapid increase in the achievable aspect ratio. Additionally, in the case of micro-walls with a thickness of 2 μm, the effect of the mold temperature on the achievable aspect ratio is slightly weaker than that of 10-μm thick micro-walls, and the maximum achievable aspect ratio is about ten. These results reveal that injection molding of micro-walls becomes more difficult as the wall thickness decreases. Moreover, if the thickness of the wall is reduced by one order of magnitude, then the mold temperature must be increased by 15 °C to yield injection molded micro-walls with a similarly high-aspect ratio. Figure 4 shows an SEM micrograph of an example of injection molded sub-micron walls with a high-aspect ratio. Micro-injection molding was finally achieved in this case by increasing the mold temperature by 150 °C, where the thickness of the sub-micron walls is approximately 0.2 μm.

The main injection pressure in the filling stage also influences the injection moldablity of micro- and sub-micron structures. Figure 5 shows the effects of main injection pressure on the achievable aspect ratio of the micro-walls. In both cases – 10-μm and 2 μm micro-walls – the achievable aspect ratios in-

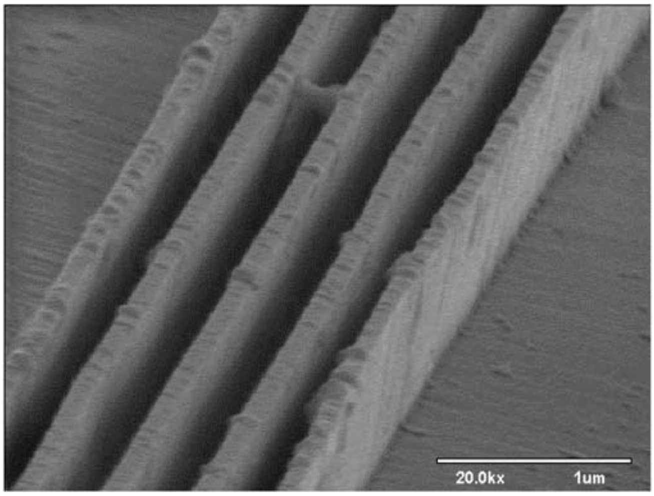


Fig. 4. SEM micrograph of an injection-molded example of PMMA sub-micron walls (molded at a barrel temperature of 250 °C, a mold temperature of 150 °C, and a main injection pressure of 120 MPa for 40 s)

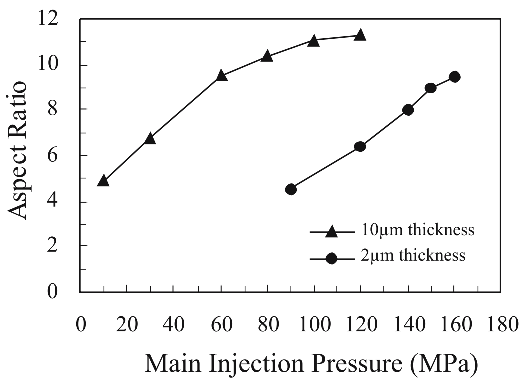


Fig. 5. Effects of main injection pressure on the achievable aspect ratio of the micro-walls (molded at a barrel temperature of 250 °C, a mold temperature of 150 °C, and a main injection time of 60 s)

crease (in principle) with the main injection pressure; however, the rates of increase of the achievable aspect ratios decline as the main injection pressure increases. Additionally, the main injection pressure in the case of 2-μm thick walls to achieve the same specified aspect ratio of the micro-walls is about 100 MPa greater than that required in the case of 10-μm walls. Figure 6 depicts the effect of time for which the main injection pressure is maintained on the achievable aspect ratio of the micro-walls. Clearly, the achievable aspect ratio of micro-walls increases with the main injection time. However, the rate of increase of the achievable aspect ratio of the micro-walls declines as the main injection time increases, and tends to zero as the main injection time rises above 30 s.

This work also investigated the effects of the other molding parameters on the injection molding characteristics of micro-walls; however, these effects are weak and can be neglected in the range of usable values of these parameters. Overall, the success of fabrication of a product with a specified high-aspect ratio micro-structure is governed by the mold temperature, the main injection pressure and the main injection time, in that order. Figure 7 presents the process window of injection molding of PMMA micro-structures. Clearly, at an acceptable high main in-

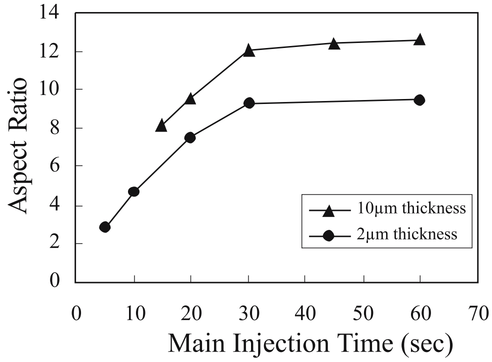


Fig. 6. Effects of main injection time on the achievable aspect ratio of the micro-walls (molded at a barrel temperature 250 °C, a mold temperature of 150 °C, and a main injection pressure of 120 MPa)

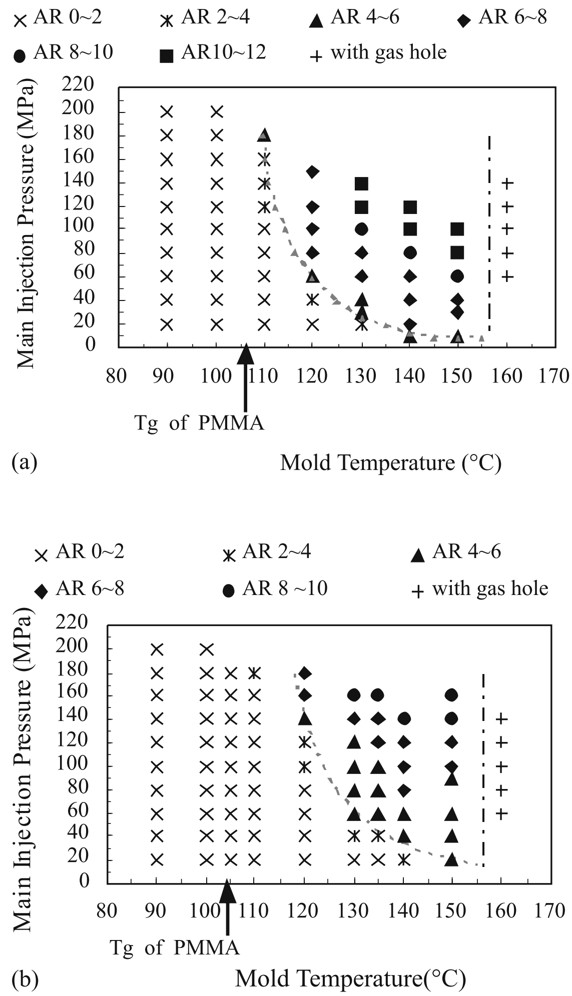


Fig. 7a,b. Process window of PMMA micro injection molding (where AR: aspect ratio, and molded at a barrel temperature of 250 °C, and a main injection time of 60 s) **a** Wall thickness of 10 μm **b** Wall thickness of 1.5 μm jection pressure that does not cause other molding problems, a mold temperature that exceeds the glass transition temperature of PMMA is required to yield micro-structures with an aspect ratio of over four. In the injection molding of a product with micro-walls with a wall-thickness of about 10 μm, the required main injection pressure will increase rapidly with the decrease of the mold temperature if the mold temperature is below 120 °C (as shown in Fig. 7a). This is a threshold mold temperature for smooth molding. Furthermore, if the specified thickness of micro-walls is reduced to about 1.5 μm, the threshold mold temperature will increase to 130 °C (as shown in Fig. 7b). However, the mold temperature should never exceed 155 °C to avoid the phenomenon presented in Fig. 2. Therefore, selecting a proper mold temperature according to the specified thickness of the high-aspect ratio micro-structure is critical to ensure that no defects are formed, to reduce the power consumption, and to shorten the cycle time.

4 Some distinctive filling behaviors and molding characteristics of micro-injection molding

The appropriate mold temperature changes with the type of polymer selected for micro-injection molding. Additionally, different polymers may yield different flow behaviors and molding characteristics. Figure 8 presents the SEM micrographs of PP short-shot in the various micro-mold cavities under suitable molding conditions. Many spherical or nipple-shaped protrusions of almost equal sizes appeared on the flow fronts of the molding material; these were not seen with PMMA. These protrusions are larger in both of the directions in which filling is not constrained by the lateral walls of micro-mold cavities; both adjacent protrusions finally meet each other, generating many weld line defects on the top surface of the molded micro-wall, as shown in Fig. 9. At intervals of several parallel micro-walls, a micro-wall is short-shot above other micro-walls, as depicted in Fig. 10, indicating that the filling speed varies greatly within the mold during the micro-injection molding of PP. Figure 11 shows an injection-molded micro-wall of HDPE. The micro-wall, which is expected to be perpendicular to the base part of the micro-walls produced, is obviously tilted, and the surfaces of both sides of the base of the micro-wall are cambered. Such a molding problem arises universally in the micro-injection molding of HDPE, but not in the case of PMMA or PP. In this work, the molding conditions less strongly affect the distinctive micro-molding characteristics of PP and HDPE, described above. Further studies based on the existing crystals and phases in the polymer should be conducted to determine the mechanisms of these phenomena.

5 Conclusions

Injection molding offers the potential of rapidly and economically generating polymer micro- and sub-micron structures of high quality. In this work, the effects of injection molding

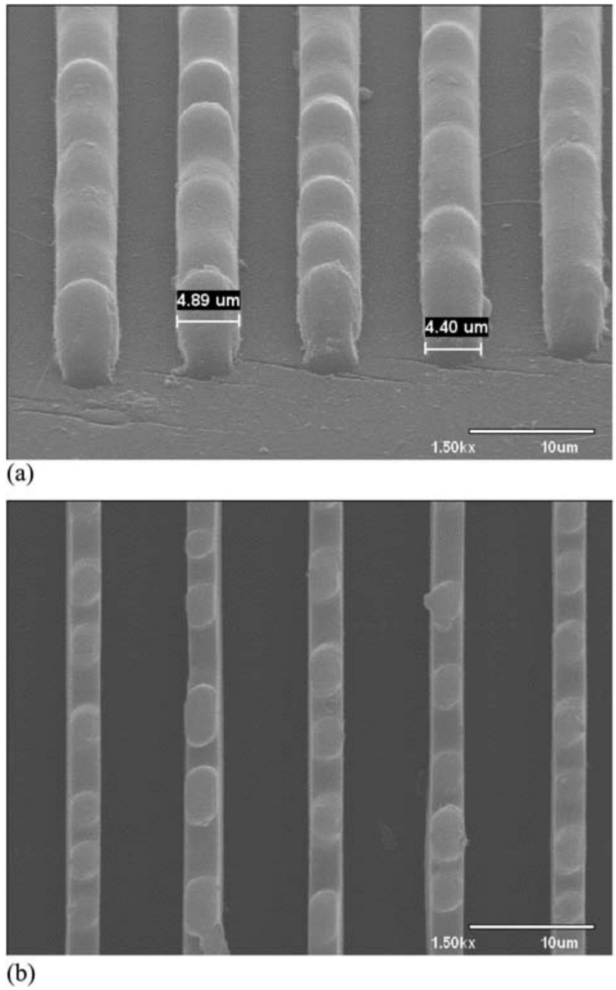


Fig. 8. SEM micrographs of PP short-shot in the micro-mold cavities. Many spherical or nipple-shaped protrusions can be observed on the flow fronts (molded at a barrel temperature of 230 °C, a mold temperature of 80 °C, and a main injection pressure of 100 MPa for 20 s)

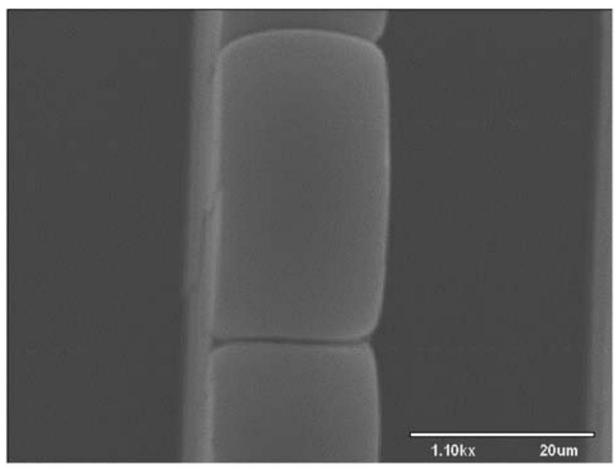
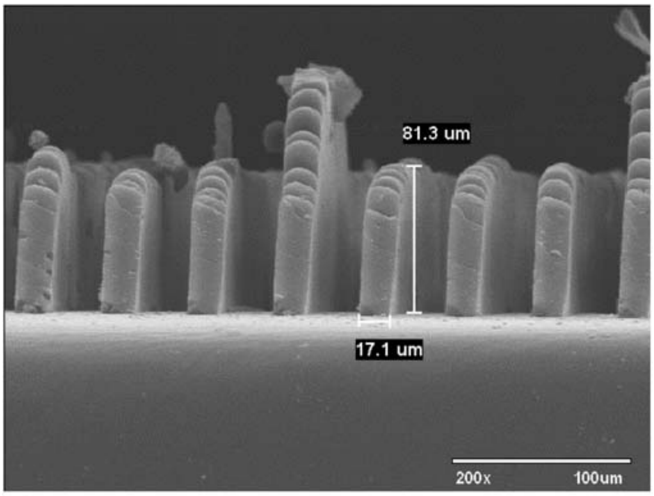
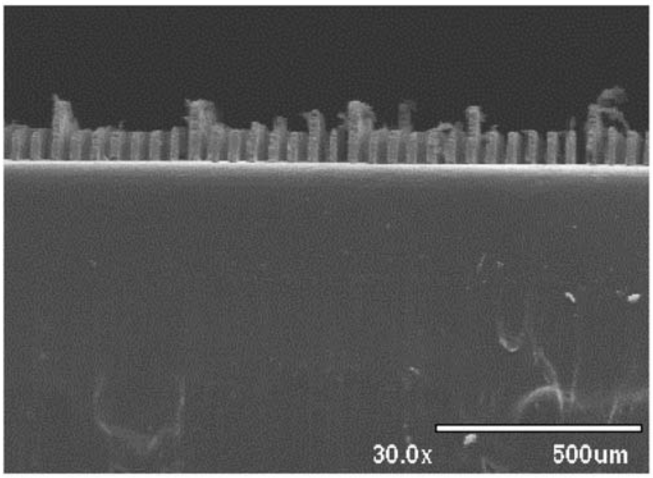


Fig. 9. SEM micrograph of the weld line defects on the top surface of the injection molded PP micro-wall (molded at a barrel temperature of 200 °C, a mold temperature of 90 °C, and a main injection pressure of 150 MPa for 25 s)



(a)



(b)

Fig. 10. SEM micrographs of a PP short-shot example, indicating that one micro-cavity is filled more quickly than the others and is separated by intervals of several micro-cavities (molded at a barrel temperature of 200 °C, a mold temperature of 90 °C, and a main injection pressure 150 MPa for 25 s)

conditions on the moldablity of micro- and sub-micron structures were considered, using the general engineering plastics – PMMA, PP and HDPE. Additionally, the distinctive filling behaviors and molding characteristics of these polymers in micro-injection molding were investigated. The following conclusions are drawn:

1. In the micro-injection molding of polymers, the mold temperature, the main injection pressure and the polymer used dominate the molding characteristics.
2. Unlike in traditional injection molding, a high mold temperature is the most important condition for the smooth injection molding of polymer micro- and sub-micron structures with a high-aspect ratio. At a sufficiently high mold temperature, the required power capacity of the injection molding machine is therefore greatly reduced. However, an excessively high mold temperature will not only reduce the productivity and increase the cost, but also cause the gasification of the polymer, forming defects caused by the remaining gas bubbles and bulges in the produced micro-structures. In the example of PMMA structures with thicknesses ranging from several 10^1 µm to 10^{-1} µm and aspect ratios that exceed two, the suggested range of mold temperatures is 120 °C to 155 °C.
3. Appropriate main-injection operating conditions (main injection pressure and main injection time) significantly increase the achievable aspect ratio of polymer micro- and sub-micron structures.
4. Some polymers such as PP and HDPE exhibit distinctive molding characteristics during micro-injection molding, which should lower the quality of the molded micro- and sub-micron structures. Further studies of the mechanisms causing these distinctive molding properties should be conducted.

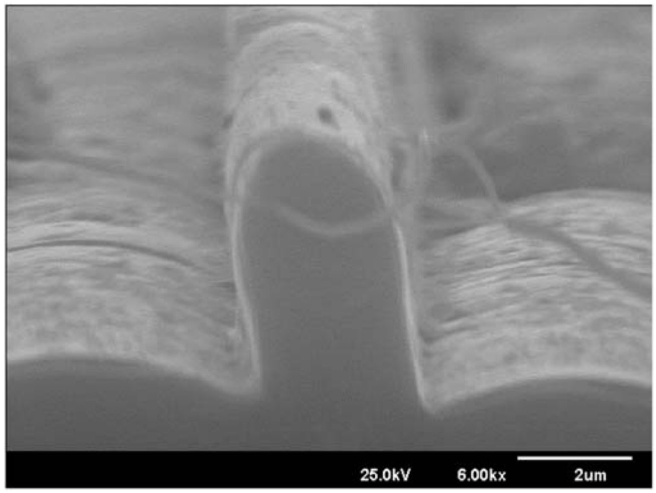


Fig. 11. SEM micrograph of an injection molded HDPE micro-wall (molded at a barrel temperature of 210 °C, a mold temperature 50 °C, and a main injection pressure 90 MPa for 20 s)

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