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TECHNICAL PAPER

Investigation of injection molding parameters on the uniformity of porous array of polymer microfluidic chip

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Abstract

The uniformity of the porous array seriously affects the performance of the injection-molded parts. In this study, a uniform hole array chip constituted by 384 holes whose radiuses are 1.30 mm is fabricated by precision injection molding technology. To capture the relevance between the uniform dimension of the porous array and the injection molding process parameters, single factor experiment was adopted. Besides, the condensed state of the hole array was studied to give a further explanation of the inner relationship between the hole array and the most sensitive injection process. As for the measurement, the diameter of the hole which next to the gate and away from the gate was investigated by means of universal tool-measuring microscope, and the standard deviation of the hole diameter was chosen to estimate the uniformity of the hole array. Furthermore, the crystal state and interface state were characterized by polarized light microscopy (PLM), used to explain why the difference of those holes appeared. The results reveal that the impact of process parameters on the uniformity of the hole array was ranked as follows: melt temperature, cooling time, mold temperature, injection pressure, injection speed and packing pressure. Besides, the analysis of the condensed state on different melt temperature indicates that the larger grain size is less favorable to the uniform molding, as the melt temperature increases, the difference of cortical thickness between the dynamic template and fixed template sides decreases, product uniformity is improved.

Keywords Uniformity · Porous array · Injection molding · Single factor experiment · Condensed state

1 Introduction

Scientists originally found inspiration from biological array structures, which have natural advantages for its repetitive structures, such as the compound eyes of insects and honeycomb structure, then it was used in radar, microwave communication, remote sensing and other fields.

At first artificial array, structure mainly took the nano materials as the substrate such as the silicon, the germanium, etc. [1]. As the polymer materials have the advantages of low cost, high performance, excellent formability and good biocompatibility [2], they are increasingly becoming the raw material of array structure. With the continuous improvement of detecting techniques, plastic parts with array characteristics have been widely applied in biomedical equipment and chemical detection devices, for example it serves as the miniature laboratory that can largely reduce the use of reagent especially for those expensive and rare cells and reagents. To date, various technologies for fabricating polymer arrays have been

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reported, such as hot embossing [3], injection compression molding and injection molding [4, 5]. Because of cost-effective benefit and mass-production capability, precision injection molding is the most potential method to satisfy the demand of plastic array devices [6].

For the development of precision injection molding technology and detecting technology, the increasingly precise, quick and massive detection results are required to keep up with pace of the biomedical technology, therefore, it is significant to research and fabricate array structure which has uniform size, shape and spatial arrangement to meet the veracity of the detection results. Various researches about array have been reported, for instance, Song et al. [7] explored the replication of large-scale micro pillar array with different diameters by micro injection molding which revealed the height of micro pillar increases with the increase of the mold temperature and injection speed. Matschuk et al. [8] explored the arrays of 40 nm wide pillars and optimized processing conditions to enhance the replication quality that is described by height, width, and uniformity of the nanoscopic feature. Chen et al. [9] studied a platform where the probes were first grafted to microbeads which were then arrayed in the microfluidic cell by capture in a trapping course. Lee et al. [10] fabricated a disposable polymer-based microneedle array by mimicking the vibrating motion of a mosquito's proboscis. Henriksen et al. [11] investigated periodic arrays of exchange-biased permalloy microstrips fabricated using a single lithography step. Until now, investigations of uniform array were mainly focused on micro array, especially for microlens array, microneedle array or nanopillar array [12–14].

The main objective of this study was to investigate the effect of injection molding parameters on the uniformity of porous array through single factor experiment and principle that the process parameters affect the uniformity.

2 Materials and methods

2.1 Materials and design

The experiments were implemented using Sumitimo SE100EV-FT injection molding machine. The polypropylene was selected as the injection-molding material for its biological and blood compatibility and excellent processability. In this paper, TOTAL polypropylene 3620WZ(Isotactic polypropylene) is selected as the experiment material, which is particularly well suited for closures, medical syringes and thin wall containers. The physical properties table of the 3620WZ is shown in Table 1.

The part is a kind of the orifice plate bracket which is used to detect the blood cells or isolate regents. Figure 1 shows the design of a hole array plate. The dimensions of the substrate are 127 mm × 85 mm × 9 mm, in which a 16 × 24 hole array (384 holes) was arranged around the 11 × 7 arc bump arrays symmetrically. The diameters of the holes are 2.60 ± 0.1 mm, and the total depth of the hole is 7 mm, but there are only 2 mm deep of the hole whose cross section is a full circle. Besides, the pitch of the array was set to 4.5 mm. Four location holes whose diameters are 4 mm are used to precisely positioning 384 hole arrays.

The cavity insert for the hole array mold was produced by CNC machining and wire electrical discharge machining, in which 384 mold cores were embedded. The corresponding mold insert was fabricated by ball end mill whose diameter was 1 mm. Furthermore, six pin point gates which were fabricated by wire electrical discharge machining were adopted to ensure the balance of the melt flow in the hole array plate. The finalized mold insert was embedded in the standard mold base, in which the feed system, cooling system and ejector system were prepared.

2.2 Single factor experiment

The single variable method was carried out with one of the process parameter values changed in turn but the others remained to analyze the effect of single process parameter on the uniformity of the hole array [7]. According to the results of Moldflow numerical simulation and properties of the material, the optimum parameters were adjusted to minimize defects, such as flash, uncompleted filling, warpage et al. [15]. Six process parameters determined by the preliminary trails were selected: melt temperature (T_{m}), mold temperature (T_{o}), injection pressure (P_{i}), injection speed (V_{i}), packing pressure (P_{p}), cooling time (t_{c}).The nominal value of process parameters were designed as follow: $T_{\mathrm{m}} = 225$ °C, $T_{\mathrm{o}} = 35$ °C, $P_{\mathrm{i}} = 1250$ kgf/cm^2, $V_{\mathrm{i}} = 30$ mm/s, $P_{\mathrm{p}} = 1150$ kgf/cm^2, $t_{\mathrm{c}} = 15$ s. Table 2 shows the detailed plan of the single factor experiment.

To analyze the uniformity of the porous array and ensure the uniformity of the sampling, thirteen groups which were near the gate, away from the gate and in the middle part of the gate were selected as the measured objects, and there were four holes in each group. Figure 2 showed the location of the thirteen groups, and the measured holes were bounded in the red rectangular. The standard deviation of the hole was chosen to estimate the uniformity of the hole array. It was defined as:

$$S = \sqrt{\sum_{i=1}^{n} (d_i - \overline{d})^2 \Big/ (n-1)}, \tag{1}$$

Table 1 The physical properties of the 3620WZ

Resin properties	Melt flow (g/10 min)	Density (g/cc)	Melting point (°C)	Tensile modulus (MPa)	Flexural modulus (MPa)	Heat deflection (°C)
Isotactic polypropylene	12	0.905	165	1725	1590	127

Table 2 The detailed single factor experiment plan

Run	P_i (kgf/cm^2)	P_p (kgf/cm^2)	T_m (°C)	T_o (°C)	V_i (mm/s)	t_c (s)
1	1250	1150	230	35	30	15
2	1210	1150	230	35	30	15
3	1330	1150	230	35	30	15
4	1390	1150	230	35	30	15
5	1430	1150	230	35	30	15
6	1250	1030	230	35	30	15
7	1250	1070	230	35	30	15
8	1250	1110	230	35	30	15
9	1250	1200	230	35	30	15
10	1250	1150	215	35	30	15
11	1250	1150	220	35	30	15
12	1250	1150	225	35	30	15
13	1250	1150	235	35	30	15
14	1250	1150	230	31	30	15
15	1250	1150	230	47	30	15
16	1250	1150	230	55	30	15
17	1250	1150	230	63	30	15
18	1250	1150	230	35	15	15
19	1250	1150	230	35	25	15
20	1250	1150	230	35	35	15
21	1250	1150	230	35	40	15
22	1250	1150	230	35	30	10
23	1250	1150	230	35	30	13
24	1250	1150	230	35	30	17
25	1250	1150	230	35	30	20

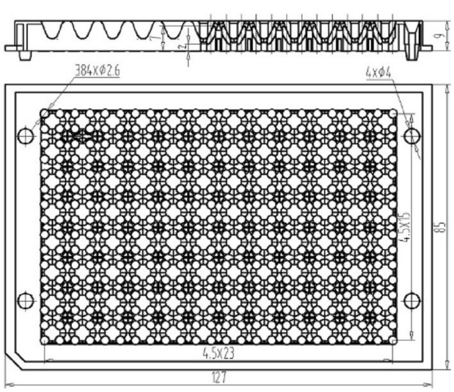

Fig. 1 The structure diagram of 384 holes array plate

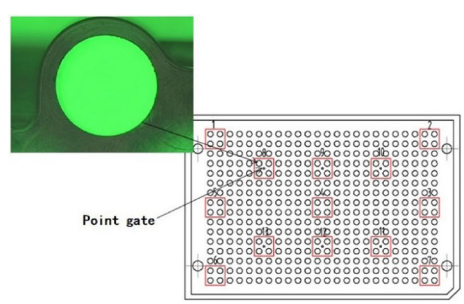

Fig. 2 The brief schematic diagram of the hole to be measured and the picture of the hole in UTM

where d_i is the diameter of the hole, n is the total number of the samples.

Furthermore, the analysis of variance (ANOVA) method was used to determine the effect of input variables on the output variables and define which input parameters highly affect the quality feature statistically. The ANOVA result of the single factor experiment was used to investigate the relation between the process parameters and the uniformity of the hole array [16]. The detailed equations are as follows:

$$P = \frac{1}{n}\left(\sum_{i=1}^{p}\sum_{j=1}^{r} d_{ij}\right)^2, \quad (2)$$

$$Q = \frac{1}{r}\sum_{i=1}^{n}\left(\sum_{j}^{r} d_{ij}\right)^2, \quad (3)$$

$$R = \sum_{i=1}^{p}\sum_{j=1}^{r} d_{ij}^2, \quad (4)$$

$$S_A = Q - P \quad S_e = R - Q, \quad (5)$$

$$f_A = p - 1 \quad f_e = n - p, \quad (6)$$

$$\overline{S_A} = S_A/f_A \quad \overline{S_e} = S_e/f_e, \quad (7)$$

$$F = \overline{S_A}/\overline{S_e}, \quad (8)$$

where d_{ij} is the diameter of the hole, n is the total number of the samples, p is the level of the featured process parameters, r is the number of samples under a certain process, S_A, S_e are the sum of the square of the diameters which comes from process parameters and experiment error, respectively, f_A, f_e represent the degree of freedom of S_A and S_e, respectively, F is the sensitivity index of each process parameter. Therefore, the effect of process parameters on the uniformity of the hole array can be explained by the corresponding sensitivity indices, which is the sensitivity index F.

3 Results and discussion

The diameter of the hole array was defined as the response variables. Each sample for measurement was randomly selected from 10 parts which were molded at the same process parameters. The universal tool-measuring microscope would be used to measure the diameter of the selected holes. Besides, crystal state and interface state of the array structure under the change of the most sensitive process parameters were characterized using polarized light microscopy (PLM). According to the measuring result of the diameters of the sampling holes, the calculation results are shown in Table 3.

Table 3 The calculations of the uniformity of the diameters

Factors	P_i	P_P	T_m	T_O	V_i	t_c
S	0.0271	0.0134	0.0115	0.0086	0.0194	0.0141
	0.0093	0.0120	0.0092	0.0093	0.0102	0.0133
	0.0117	0.0113	0.0093	0.0089	0.0093	0.0093
	0.0082	0.0093	0.0106	0.0093	0.0113	0.0103
	0.0140	0.0108	0.0086	0.0103	0.0103	0.0122
S_A	0.0051	0.0024	0.0058	0.0021	0.0031	0.0061
S_e	0.0623	0.1285	0.0307	0.0221	0.0409	0.0366
F	5.2188	1.1907	12.0442	6.0554	4.8438	10.6250
Rank	4	6	1	3	5	2

The critical value of the significant level is 3.32 [16]. The sensitivity index of the process parameters calculated by Eq. (8), as presented in Table 3, indicated that those process parameters have different effects on the uniformity of the hole array, in which melt temperature and cooling time represents extremely significant effect on the uniformity of the array structure, mold temperature, injection pressure, and injection speed represents significant effect, and packing pressure represents no great impacts.

3.1 Analysis of the uniformity of the hole array by single factor experiment

The standard deviation of the hole diameter varies with each process parameter as shown in Fig. 3.

As shown in Fig. 3f, the uniformity of the hole diameter of the porous support substrate increases as the melt temperature increases, due to the increase in melt temperature, which contributes to improved melt flow. In addition, an increase in the melt temperature is advantageous in reducing the post-shrinkage of the parts to improve the uniformity of the array.

As the cooling time increases, the standard deviation of the hole array decreases first and then increases. This indicates that the uniformity of the molding quality of parts increases with the increase of the cooling time in a certain period of time, but the cooling time of crystalline plastic is generally shorter, PP that is crystalline plastic, so the cooling time should not be too long. Figure 3d indicates that 15 s is the optimal value of the cooling time for the uniformity of the array structure.

Mold temperature, injection pressure and injection speed has significant effect on the uniformity of the array structure. Figure 3e indicates that increasing the mold temperature will increase the uniformity of the array products in a certain temperature range. However, the polypropylene used in the substrate is a crystalline plastic,

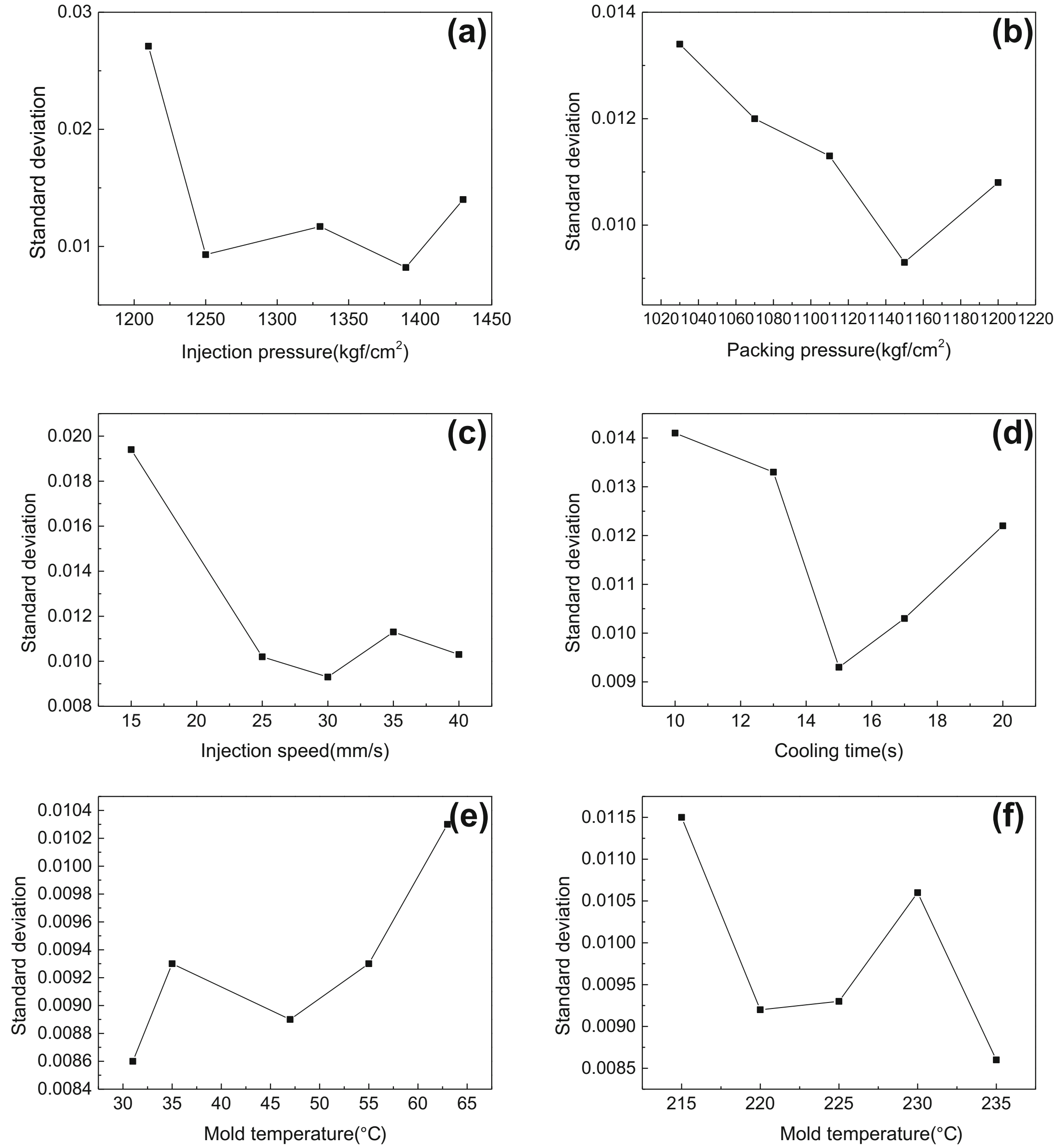

Fig. 3 The line chart of each process parameter and calculated results

and the glass transition temperature is low. As the mold temperature continues to increase, the post-crystallization phenomenon occurs, which leads to the post-shrinkage and performance change of products. With the increase of the injection pressure, the standard deviation changed just as shown in Fig. 3a. The increase of the density of plastic parts makes the linear expansion coefficient decrease, the total shrinkage decreases. Subsequently, as the injection pressure increases, the uniformity of the array products is reduced, which is due to injection pressure that is too large, not only caused the mold flash, but also lead to products great internal stress, causing deformation, the uniformity of molding quality is deteriorated. In our experiment, 1390 kgf/cm^2 would be an optimum value for the uniform forming of array structure. Moreover, as shown in Fig. 3c, with the increase of injection speed, the uniformity of product forming is improved, which is due to the increase of injection speed that can make the flow velocity of the melt in the flow channel and mold cavity increase, a strong shear effect of the melt temperature quickly makes viscosity decrease, so the product weld line becomes strength, shrinkage is down, and the molding accuracy of products is improved. The proper injection speed is 40 mm/s for the uniformity of the hole array. Packing pressure almost has no great impacts as other process parameters for the uniformity of the array structure, the proper value is 1150 kgf/cm^2, which has the best matching effect with other process parameters.

3.2 Analysis of the condensed state on the most sensitive process parameter

To further study the mechanism of the molecular condensation state of the process parameters on the uniformity of the array formation, the polarized light was analyzed by taking the melt temperature with the greatest influence on the uniformity of parts. First of all the products need to be sampled at 215, 220, 225, 230 and 235 °C, divided into 5 groups and then sampled from the pouring position. Finally, along the melt flow direction(FD), equidistant selection of two positions, slice thickness is 30 μm, as shown in Fig. 4.

Figure 5 is the morphology of sliced samples taken under tool microscope and polarized microscope. It can be seen from the polarized image that the injection-molded porous support substrate has a layered phenomenon in which the outermost layer is a cortex formed near the wall of the cavity and has a spherulite structure. As the internal shear effect of the melt is small, the cooling rate is also small, the orientation of the molecular chain can be relaxed to the solution to form a spherulite structure.

Figure 6(1–1) shows the first group of experiments that the sample polarized detection image at the point gate in the melt temperature of 215 °C, 1–2 is samples slices of the middle position along the melt flow direction when the melt temperature is 215 °C, 1–3 is slices at the furthest in the temperature of 215 °C. The picture is Photoshop grayed out for easy comparison.

From Fig. 6, we can see: at different melt temperatures, the thickness of the cortex on the fixed template side is greater than that of the dynamic template side. The thickness of the cortex on the fixed template side is constantly thinning, simultaneously, the thickness of the cortex on the dynamic template side is gradually thickened along the direction of the melt flow and the thickness difference of the cortex is decreasing. This is due to the strong role of the shear at the pointing gate, shear heat makes the mold temperature difference of both sides of mold greater, resulting in a larger cortex thickness difference.

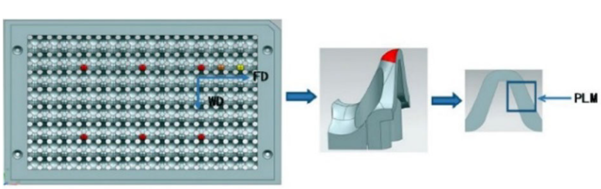

Fig. 4 The sampling way of PLM analysis

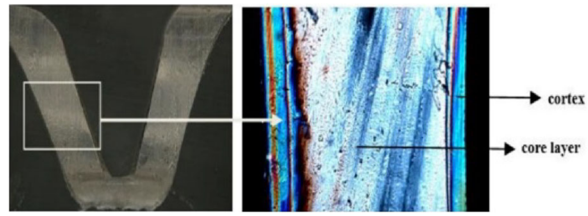

Fig. 5 The morphology of samples under different microscope

At different melt temperatures, using a polarizing microscope whose magnification is 500 times to observe the crystal morphology of slices at the gate shown in Fig. 7, from the figure you can see the typical cross extinction spherulite structure, and the results show that the uniformity of 230 °C is poor, so the larger the grain size is, the worse the uniformity is.

Polarization analysis shows that the melt temperature mainly affects the uniformity of parts through the change of the condensed state of the internal macromolecule chain. The improvement of the melt temperature is beneficial to the uniformity. However, when the temperature is 230 °C, the grain size is relatively large, is not conducive to the uniform shape of the product. The optimum melt temperature is 235 °C by analysis of the cortical thickness and grain size.

4 Conclusion

This paper reports an experimental investigation of process parameters' effects on the uniformity of the porous array structure. Using single factor experiment, the relevance of the uniformity of the hole array and process parameters was studied. Furthermore, analysis of the condensed state of the array structure was used to explain the inner relationship of the most sensitive process parameter on the hole array. Besides, an optimum process parameters were selected to get a uniform array structure, which will contribute to improving the detection precision of the biomedical chip. The main conclusions are as follow:

1. There is a close relationship between the uniformity and process parameters. Mold temperature and injection pressure have an extremely significant effect on the uniformity of the array, melt temperature, injection speed have significant effect, cooling time has a certain effectiveness, and packing pressure almost has no great impacts as other process parameters.
2. The thickness of the frozen layer and the shear layer decreased, and the thickness of the core layer increased gradually. The change of the mold temperature will

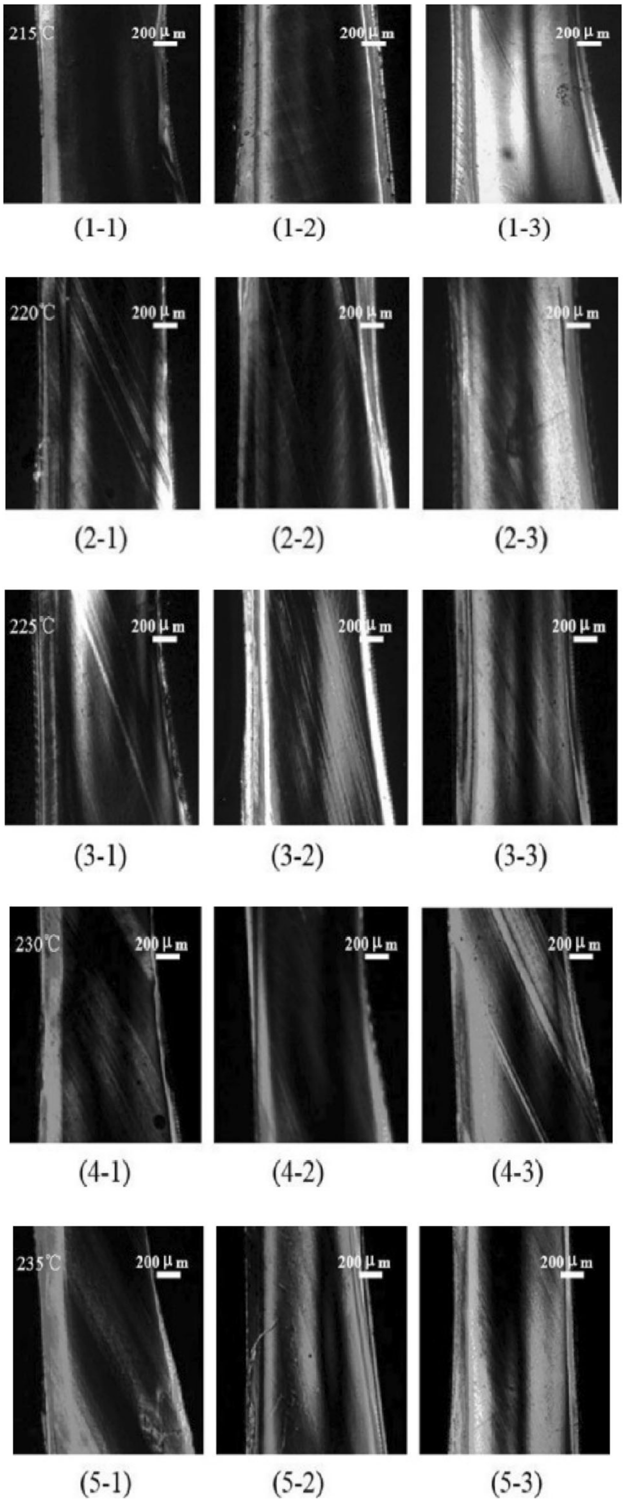

Fig. 6 The interface state at different melt temperatures along the melt flow direction in PLM

affect the stretch direction and orientation of the molecular chain, which will directly affect the crystal morphology of the subsequent evolution. It explained the shrinkage difference of the hole array, which was

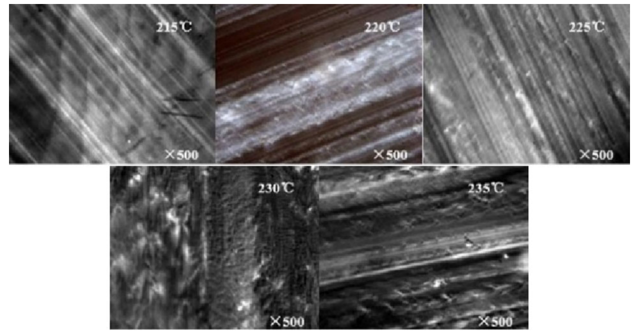

Fig. 7 The crystal morphology in different melt temperature

the essence of the melt temperature influencing the uniformity of the array structure.

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References

1. Cummins C, Gangnaik A (2015) Parallel Arrays of sub-10 nm aligned germanium nanofins from an in situ metal oxide hard-mask using directed self-assembly of block copolymers. Chem Mater 27:6091–6096
2. Song M, Liu Y (2013) Research on incorporate injection molding of the cover sheet and the substrate sheet for microfluidic chip. Mater Sci Technol 21:13–17
3. Konstantinou D, Shirazi A (2016) Combined hot embossing and milling for medium volume production of thermoplastic microfluidic devices. Sens Actuat B Chem 234:209–221
4. Metwally K, Barreiere T, Khan-Malek C (2016) Replication of micrometric and sub-micrometric structured surfaces using micro-injection and micro-injection compression molding. Manuf Technol 83:779–789
5. Packianather M, Griffiths C, Kadir W (2015) Micro injection molding process parameter tuning. Proc CIRP 33:400–405
6. Hong S-Z (2005) Precision injection molding and factor of mold designing. Die Mould Technol 4:24–33
7. ManCang S, Hui Z, Shan LJ (2016) Replication of large scale micro pillar array with different diameters by micro injection molding. Microsyst Technol 10:1007–1016
8. Matschuk M, Larsen NB (2013) Injection molding of high aspect ratio sub-100 nm nanostructures. J Micromech Microeng 23:1–10
9. Chen X, Leary TF, Maldarelli C (2017) Transport of biomolecules to binding partners displayed on the surface of microbeads arrayed in traps in a microfluidic cell. Biomicrofluidics 11:1–23
10. Lee F-W, Hung W-H, Ma C-W, Yang Y-J (2016) Polymer-based disposable microneedle array with insertion assisted by vibratingmotion. Biomicrofluidics 10:1–11
11. Henriksen AD, Rozlosnik N, Hansen MF (2015) Geometrical optimization of microstripe arrays for microbead magnetophoresis. Biomicrofluidics 9:1–14
12. Xiahui W, Hongwen R, Qionghua W (2016) Polymer network liquid crystal (PNLC) lenticular microlens array with no surface treatment. J Disp Technol 12:773–777
13. Lihong N, Xiaohong J, Yaolong Z (2016) Large-area, size-tunable Si nanopillar arrays with enhanced antireflective and plasmonic properties. Nanotechnology 31:1–9

14. Wenggang W, Haiyang M, Xiang H (2016) Fabrication and characterization of SiO_2/Si heterogeneous nanopillar arrays. Nanotechnology 30:1–9
15. Lixia W, Bei W (2003) Research on the influence of process parameters on quality of injection molding products. J Zhengzhou Univ 24:62–66
16. Group of Mathematical Statistics in Institutes of China (1977) Analysis of standard deviation. Science Press, Beijing, China