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Effects of process parameters on the molding quality of the micro-needle array

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Abstract. Micro-needle array, which is used in medical applications, is a kind of typical injection molded products with microstructures. Due to its tiny micro-features size and high aspect ratios, it is more likely to produce short shots defects, leading to poor molding quality. The injection molding process of the micro-needle array was studied in this paper to find the effects of the process parameters on the molding quality of the micro-needle array and to provide theoretical guidance for practical production of high-quality products. With the shrinkage ratio and warpage of micro needles as the evaluation indices of the molding quality, the orthogonal experiment was conducted and the analysis of variance was carried out. According to the results, the contribution rates were calculated to determine the influence of various process parameters on molding quality. The single parameter method was used to analyse the main process parameter. It was found that the contribution rate of the holding pressure on shrinkage ratio and warpage reached 83.55% and 94.71% respectively, far higher than that of the other parameters. The study revealed that the holding pressure is the main factor which affects the molding quality of micro-needle array so that it should be focused on in order to obtain plastic parts with high quality in the practical production.

1. Introduction

At present, the rapid development of microsystem technology sets higher requirements for the manufacturing of micro parts. An efficient manufacturing processes of micro parts with low-cost, reliability and stability is expected [1]. As a key technique for microsystems, micro-injection molding process is available for manufacturing micro components. It offers the capability to massively produce micro components with relatively low costs and short-cycle times, and the potential for full automation and accurate replication [2]. Therefore, micro-injection molding process attracts more and more attentions home and abroad. There is no wonder that its products which are called micro-molded parts are widely applied in information and communication technology, medical and biotechnology, micro-sensor technology and daily life [3].

The concept of micro-needle was put forward in the 1970s. Due to the limitation of process conditions, micro-needle was not applied in transdermal drug delivery and blood extraction fields until 1998. In recent years it started to get wide attentions. Micro-needles can be characterized into two groups [4]: (1) in-plane design where the micro-needle shank is in the same plane as the substrate and (2) out-of-plane design where micro-needles are made perpendicular to the substrate. With the development of various technologies, micro-needles or micro-needle arrays with different types and different sizes have been researched and manufactured. Sammoura et al. used plastic injection molding to fabricate an in-plane, open-channel micro-needle [4]. Mold insert temperature control is identified as the major reason for the discrepancy between experiments and simulation results. Sha et al. investigated the effects of three process (barrel temperature, mold temperature and injection speed) and one geometric factors on the surface quality of micro-pins in three different polymer materials [5]. The experimental results revealed that the effects of these factors on the process replication capabilities are not consistent for different polymer materials. Zhang and Lu analyzed the morphology and performance of polypropylene (PP) microstructures manufactured by micro injection molding and fabricated micro-needles with ϕ130μm×depth 250μm dimensions [3].

Micro-needle arrays belong to micro components with high surface-to-volume ratios and high aspect ratios. Compared with conventional injection molding, micro-injection molding is confronted with large challenges and more difficulties, which leads to micro parts with poor replication quality. In addition other micro-molded parts face the same problem. Many studies that used different experimental conditions and test parts including micro-needles were carried out [6]. The results showed that individual process parameter has a significant effect on the molding quality of the produced components. Sha et al. studied the effects of five process (barrel temperature, mold temperature, injection speed, holding pressure, the existence of air evacuation) and one size factors on the achievable aspect ratios, and the roles they play in producing micro components in different polymer materials [7]. The results revealed that the barrel temperature and the injection speed are key factors affecting the aspect ratios of micro features replicated in PP and Acrylonitrile-Butadiene-Styrene (ABS). Lin and Young observed that compared with increasing holding pressure, increasing mold temperature is more effective to improve the polymer melt to fill into the microstructure with high aspect ratio [8]. Zhao et al. found that metering size and holding time are the process parameters that have the most significant effects on part quality [1].

In this paper, the injection molding process of the micro-needle array was studied and the orthogonal experiment and the contribution analysis were carried out. The shrinkage ratios and warpages of micro needles under different process conditions were compared to find the effects of the process parameters on the molding quality of the micro-needle array. The single parameter method [9], namely one parameter changed while the rest of the parameters kept constant, was used to analyze the significant process parameter to provide theoretical guidance for practical production and to realize the goals of high quality, low costs and low rejection ratio.

2. Molding defects

Due to the molding material characteristics, the cavity complexity, the machine performance and the process parameters, molding defects appear inevitably in the plastic parts, such as short shots, bubbles, weld lines, ring grooves, warpage, shrinkage and stress marks. The molding quality, particularly the shrinkage and the deformation of the micro needles, will have a great influence on the part demolding behavior. Because of the shrinkage and deformation of the molded parts, the contact pressure between the part and the mold may increase [10]. Moreover, the part-mold friction force becomes lager, leading to a difficult demolding behavior. The needles may be damaged and seriously fractured. Therefore, deformation and shrinkage are the defects that cannot be ignored in the process of injection molding, which need to be studied deeply.

2.1. Shrinkage

The shrinkage refers to the reduction of the shape size caused by the characteristic of heat-expansion and cold-contraction, the elastic recovery of the plastic and demolding deformation. According to the shrinkage ratios, the plastic parts can match well with the original size to ensure product sizes within the tolerances of the cavities [11].

2.2. Warpage

The phenomenon that the shapes of the plastic parts deviate from the mold cavity boundaries is called warpage deformation [11]. It is one of the common defects which appear in plastic parts. With the development of the plastics industry, the appearance quality and functional performance of plastic parts meet with higher and higher requirements. As one of the most important indices to evaluate the quality of the products, warpage deformation attracts more and more attention.

3. Experimental setup

3.1. Test part design and material

Figure 1 presents a micro-needle array whose diameter and height is ϕ100μm and 1mm respectively, perpendicular to a substrate whose diameter and height are 5mm and 1mm respectively. The micro needles are regarded as the microstructures. The number of micro-needle array is set 3×3 for convenient analysis and low computational complexity.

The dimension of the micro needles is in the micrometer range while that of the substrate is in the millimeter. Due to the great gap in size between micro-needle and substrate, the difficulty for the injection molding of the micro needles becomes much larger. Short shots and deformation defects are easier to arise, leading to bad needles with poor quality. As a result, the effect mechanism of process parameters on the molding quality must be clear in order to obtain micro-needle arrays with high quality.

A commonly used material in injection molding, PP is selected to conduct the planned experiments. Due to its good flowability and stability, PP is widely used for spring elements, clips, gear wheels, and small machinery products.

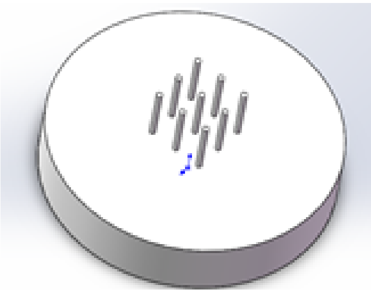
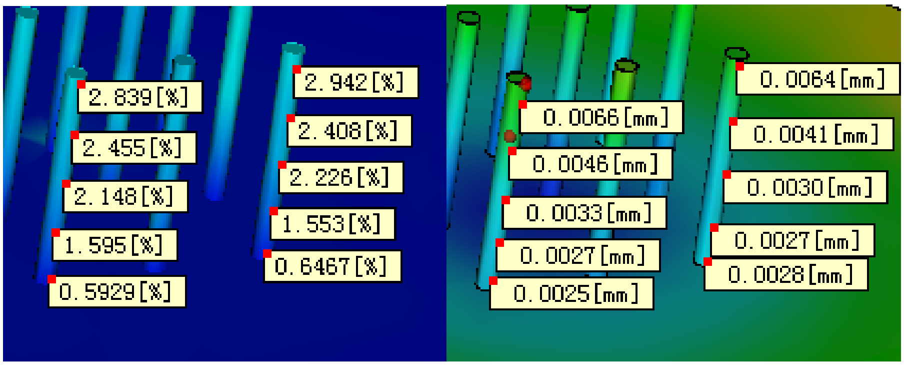


Figure 1. The micro-needle array model obtained through the SolidWorks software

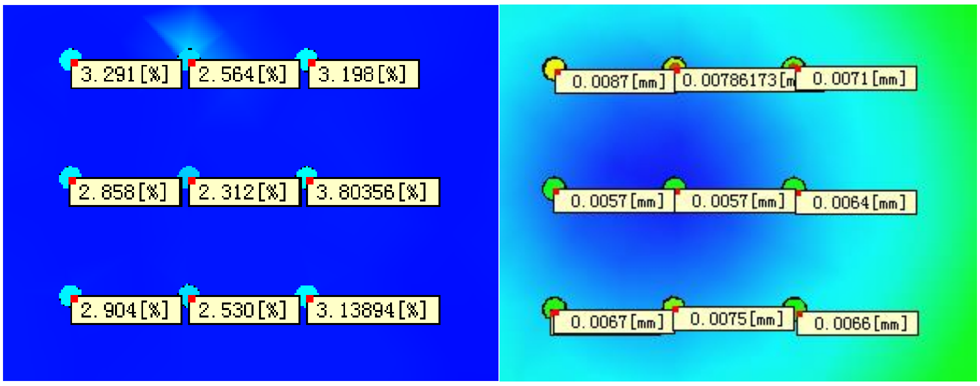
3.2. Evaluation indices

To investigate the effects of the processing parameters on part replication, this experimental research was focused on the shrinkage ratio and the warpage of the micro needles.

From the bottom to the top of a micro needle, the shrinkage ratio and the warpage are both increasing gradually (shown in figure 2. (a) and (b)). Because the shrinkage ratios and warpages of all the needles are different, we can't use a needle's values to represent the entire value of the array. In order to better describe the shrinkage ratios and warpages of the entire array and reduce the data contingency, we take the averages of top values as the evaluation indices as shown in figure 2. (c) and (d). All the values were obtained under the same process condition that the injection speed, mold temperature, melt temperature, holding pressure and holding time is 40mm/s, 40° C, 220° C, 40MPa and 4s respectively.



(a) (b)



(c) (d)

Figure 2. The shrinkage ratios and warpages of micro needles

3.3. Design of experiments

As the significant parameters, injection speed (S), mold temperature (Tmol), melt temperature (Tm), holding pressure (P) and holding time (T) were investigated in this study. Several pre-experiments were conducted before the orthogonal experiment to get the processing windows and promise complete filling.

According to the levels of each factor (table 1), a L16 orthogonal experiment (table 2) was conducted to reduce the trial numbers without repetition and to ensure that the experimental results were representative of the considered processing windows for the selected material [7].

Table 1. The experimental factors and levels

Factors / levels	S(mm/s)	Tmol(°C)	Tm(°C)	P(MPa)	T(S)
1	40	40	220	40	4
2	60	55	235	60	6
3	80	70	250	80	8
4	100	85	265	100	10

3.4. Results and analysis

From table 2, it is obviously observed that as the parameters change, the shrinkage and warpage of the micro-needle array both have different changes. To find the significant process parameters affecting the molding quality, a contribution analysis method was used. First, we finished analyzing variance through the orthogonal assistant software. After getting sum of square of deviations (Q) of a factor, we calculated its contribution rate. The contribution rate refers to the proportion of the factor's Q to the sum of each factor' Q. The contribution rates of each parameter on shrinkage ratio and warpage were calculated according to the following equations and listed in table 3.

$$Qs = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$$

$$R_n = \frac{Q_n}{Qs} \times 100\%, n = 1, 2, 3, 4, 5$$

Q is sum of square of deviations of a factor, R*n* is the contribution rate of the factor.

Table 2. The results of the L16 orthogonal experiment

trials	S	Tmol	Tm	P	T	Shrinkage ratio (%)	Warpage (μm)
1	1	1	1	1	1	2.956	6.92
2	1	2	2	2	2	2.714	7.10

3	1	3	3	3	3	2.236	4.96
4	1	4	4	4	4	2.220	5.86
5	2	1	2	3	4	0.574	2.24
6	2	2	1	4	3	7.134	11.49
7	2	3	4	1	2	2.492	6.70
8	2	4	3	2	1	3.346	8.39
9	3	1	3	4	2	2.829	6.86
10	3	2	4	3	1	2.293	5.50
11	3	3	1	2	4	3.902	9.81
12	3	4	2	1	3	2.889	8.64
13	4	1	4	2	3	3.207	7.82
14	4	2	3	1	4	3.221	7.60
15	4	3	2	4	1	3.040	6.30
16	4	4	1	3	2	2.643	5.93

Table 3. The contribution rates of each parameter on shrinkage ratio/warpage.

Factors	sum of square of deviations(Q)	degree of freedom	Standard Deviation	Contribution rate （%）
S	1.050/1.830	3	0.350/0.610	8.61/2.67
Tmol	0.293/0.635	3	0.064/0.212	2.41/0.93
Tm	0.211/0.145	3	0.070/0.048	1.73/0.21
P	10.184/64.778	3	3.395/21.59	83.55/94.71
T	0.451/1.010	3	0.150/0.337	3.70/1.48
Sum(Qs)	12.189/68.398	15		

From table 3, we can find that each parameter has an effect on the shrinkage and warpage of the micro-needle array. But, the degrees of effect are different. The contribution rate of holding pressure on the shrinkage ratio and warpage are 83.55% and 94.71% respectively, much higher than the other parameters. This indicates that holding pressure is the most significant factor affecting the molding quality of the micro-needle array. In practical production, holding pressure should be focused on in order to obtain plastic parts with high quality.

4. Effects of holding pressure on molding quality

In the previous section, combined with the orthogonal experiment and the contribution analysis method, the holding pressure was found to be the most significant process parameter affecting the molding quality of the micro-needle array. In order to know how the holding pressure affects the molding quality clearly, a single parameter experiment on holding pressure, namely the holding pressure changed while the rest of the process parameters kept constant, was designed and conducted, expecting to provide feasible theoretical guidance for practical production and reduce rejection rate.

The holding pressure refers to the injection molding pressure on the melt in the holding phase. It can help to reduce the shrinkage, improve the density of plastic parts and overcome the defects on the surface of the plastic [11]. At the same time, it can also prevent the reverse flow of melt in the cavity.

In the experiment, other process parameters were kept constant and only holding pressure was changed. The process condition was：Injection speed 60mm/s, Mold temperature 55°C，Melt temperature 235°C and Holding time 4s. Figure 6 presents the change of shrinkage ratio and warpage obtained through the same method in the section 3.2.

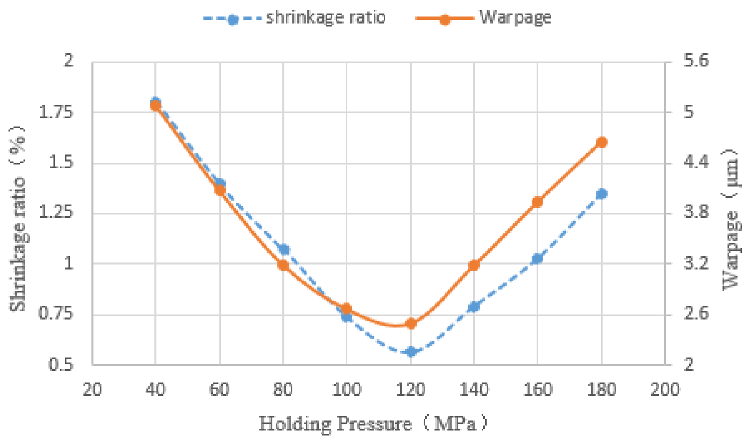


Figure 3. The variation trends of the Shrinkage ratio and warpage on holding pressure

In figure 3, the shrinkage ratio and warpage value of the micro needle array both present a parabolic trend with continuous increase of the holding pressure. Due to the shrinkage of the melt in the cavity, gap appears between the melt and the mold. The purpose of the holding stage is to drive a small amount of melt into the cavity to compensate the gap and ensure the cavity wholly filled [12]. In the experiment, the peak value of the injection pressure was observed to be a constant value when the mold temperature, melt temperature and injection speed were all kept constant, no matter how the holding pressure and holding time were changed. Because of the characteristic of heat-expansion and cold-contraction, the melt in cavity will shrink quickly with the heat loss. And the gate cools and solidifies in a short time. Therefore, if the holding pressure is low at this point, the cavity will not get sufficient melt before the gate solidifies absolutely. As a result, high shrinkage ratios and warpages will arise in the micro-needle array. With the continuous increase of the holding pressure, the pressure transfers effectively in the cavity to make more melt flow into the cavity to reduce shrinkage and warpage. The pressure can drive a large quantity of melt into the cavity when it exceeds a certain value, leading to part expansion, which also causes obvious warpage deformation. Combined with the variation tendency of the shrinkage ratio and the warpage versus the holing pressure, the conclusion can be obtained: increasing the holding pressure can effectively decrease the shrinkage ratio and the warpage of the micro-needle array. However it should be noted that too much pressure will not only lead to part expansion but also incur higher requirements for the equipment. Of course, in practical production, the holding pressure must be given at an appropriate value, neither too high nor too low, to reduce shrinkage and warpage as much as possible.

5. Conclusions

Micro-needle array is a kind of typical injection products with microstructures. Owing to its tiny micro-features size and high aspect ratios, it is more likely to produce short shots and deformation defects, leading to poor molding quality during micro injection molding. The injection molding process of micro-needle array was studied in this paper to find the effects of the process parameters on the shrinkage ratio and warpage of the micro-needle array and to provide theoretical guidance for practical production of high-quality products, combined with the orthogonal experiment and the contribution analysis method. The study showed that the shrinkage ratio and the warpage are both increasing from the bottom to the top of the micro needles gradually. The holding pressure was proved to be the most significant factor affecting the molding quality, whose effectiveness is much larger than that of other factors. The shrinkage ratio and warpage value of the micro-needle array both displayed a parabolic trend with the continuous increase of the holding pressure, reaching a minimum value at one point. When the holding pressure is too low, the cavity can’t get enough melt to be completely filled, leading to obvious shrinkage and warpage deformation. Then the phenomenon gets improved as the holding pressure rises. When the pressure exceeds a certain value, the melt is compressed excessively. This can cause part expansion and obvious warpage deformation. Therefore, the holding pressure should be focused on in order to reduce the shrinkage and warpage and obtain plastic parts with high quality in the practical production.

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