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Micro injection moulding process parameter tuning

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Abstract

This paper focuses on tuning the micro injection moulding process parameters. In this study four process parameters namely, barrel temperature, mould temperature, holding pressure and injection speed were considered. In order to capture their behaviour a L16 Orthogonal Array with two levels for each parameter was employed to produce the design of a 15 mm x 20 mm x 1 mm microfluidic platform using Cyclic Olefin Copolymer (COC), a common polymer. The demoulding force was measured during the micro injection moulding process. The sixteen trials were repeated ten times to incorporate process variation, systematic and random noise in the experimental procedure. The results were analysed using Taguchi method to identify the influence of the process parameters upon the demoulding force and their sensitivity to noise. In addition, the results also indicated either the presence or absence of the two level interactions between these process parameters. This study has contributed to understanding the characteristics of these process parameters in terms of their main effects, interactions and sensitivity to noise and to tune them for their optimal performance.

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Keywords: Micro injection moulding, design of experiments, orthogonal array, Taguchi analysis.

1. Introduction

There is rapid improvement in micro-engineering technologies which leads to an increasing trend towards product miniaturisation. Components and products in micro/meso scale are gaining importance significantly in areas like communication, IT, health care, automotive sectors and consumer goods. Moreover, the development of new miniaturized products including medical and biotechnology give microtechnologies an important role in facing the macro and nano worlds [1, 2]. Micro Injection Moulding (MIM) is a reliable replication technique and economic in producing a wide range of micro components such as micropumps, microgears, and optical grating element in large quantities. In all of these applications, the quality of the micro features found on the replicated parts is a factor which influences the reliability of the selected replication process. This depends greatly on their size, aspect ratio, and overall geometry [3].

The surface quality achievable and aspect ratio in replicating the micro features underline the important characteristic of any micro fabrication process and determine the manufacturing restriction of a given process or material combination [4]. For example, the surface quality and edge definition must be carried out systematically. In addition, achieving a high aspect ratio to mould micro features is still difficult [5]. Thus, in micro injection moulding process it is very essential to understand the factors that affect the replication capabilities [4].

To improve the quality in replication process of micro injection moulding, many research groups have investigated different areas like processing, tooling innovation, materials and insert manufacture. Although the high setting of melt temperature, mould temperature and injection speed are considered as the best result for producing quality parts the consequences on high mould temperature introduces tool innovation for heating and cooling the tool [6]. Hence, process output decreases and the cost of the moulded parts increases.

Demoulding is one of the micro injection processes that affect the quality in replication. When a replicated part reaches a stable solid form inside the mould, a series of ejector pins will forcibly eject the part out from the replication tool. Suitable amount of force are needed to overcome the retarding forces which build up at the tool interface and component due to friction and adhesion. During development of tooling in

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injection moulding designers endeavour to optimize replication tool to minimize the demoulding force and resultant stress on replicated parts.

Previous research on micro injection moulding has shown that a high mould temperature is most important in achieving good quality of replication part but it increases the cost and time. Hence, an appropriate determination of mould temperature is essential to improve quality and output, and reduce the cost. In this paper, a design of experiment is used to establish the parameter levels that affect the micro injection moulding in their replication capabilities. In this study, the following process parameters such as temperature of barrel, temperature of mould, holding pressure and injection speed into mould were considered. Demoulding force was used as the measured output for setting the level of process parameters. The twofold objectives of this study were: to investigate the level of main process parameters which affect the demoulding force in order to achieve a good quality in the replication of parts; and to understand the effect of process parameters on the micro injection moulding process.

The paper is organized as follows. The micro injection moulding process is described in section 2. The experimental procedure is explained in section 3. In section 4 the results and analysis of the results are presented. The paper is concluded in section 5.

2. Micro injection moulding

Researchers have given the definition of micro injection moulding as process for producing polymetric parts with structure dimensions in the micron or sub-micron range [7]. Component parts that have been manufactured by micro injection moulding fall into one of the following categories which are type A having sizes of overall dimension less than 1 mm and type B having larger sizes on overall dimension but incorporate micro features with sizes typically smaller than 200 µm [5]. Micro injection moulding has similar basic steps with conventional injection moulding. Typically conventional injection moulding stages consist of filling, packing, holding and cooling phases. The micro injection moulding starts from closing the mould, followed by polymer being injected into the mould, after which holding and cooling takes place until the polymer is solidified, lastly the mould opens and ejects the part from the mould. The injection stage requires plasticization of polymer material as the polymer melts and fills the mould cavity. At holding stage, the holding pressure secures the melt from escaping from the mould cavity and allows the melt for additional shrinkage. The cooling stage starts from the end of holding pressure until the mould is open [8]. The cooling process is essential as to solidify the polymer before it gets ejected from the mould in one piece. The parameters of micro injection moulding and conventional injection moulding are the same which are mould temperature, holding pressure, injection speed, holding and cooling time.

2.1. Replication capability of process parameters

The micro injection moulding process has many factors which affect its replication capability. Therefore, many researchers have studied the significance of this process parameters such as melt and mould temperature, injection speed into mould, and holding pressure. The recent developments in micro injection moulding machine have enabled the introduction of specially designed systems for the fabrication of miniature parts incorporating micro features. At the same time in an attempt to improve the process performance, new process parameters such as the metering size and a small forward movement of the injection plunger for controlling the holding pressure have been considered [9]. Previous researchers who looked into the conventional injection moulding process have identified the melt and mould temperature, injection speed and pressure as the the main factors due to their effect on melt flow property.

In some cases there were differences within the findings. This could be explained by different experimental conditions such as different sizes of test parts and polymers which were used. Although, high settings of process parameters like high melt and mould temperature can be used to improve the melt flow in micro cavities, it can also generate negative effects on the injected parts [4, 6]. A high melt temperature could increase the rate of degradation of polymer, high mould temperature may increase the cycle time and cost for cooling equipment and high injection speeds can result in high pressure at the screw tip causing material degradation [10].

In recent research, process parameters such as melt temperature, mould temperature, injection speed, and holding pressure which influence the pressure in cavity of micro injection mould were investigated [11]. Hence, a design of experiment is needed to determine an optimum level of process parameters necessary for tuning the MIM process.

2.2. Polymers in micro injection moulding

There are many types of polymer materials that have been used in micro injection moulding for a variety of micro component parts in industry. Researchers have been using various types of polymers in their studies for better understanding of the behaviour of those polymers in micro injection moulding process. Polymers are known for their low cost and good electrical, mechanical and optical properties. The flow and thermal properties of polymers are the main reason for their usage in injection moulding although it can affect the replication capabilities and quality of moulded parts. Further, micro cavities can lead to strict dimensional limits and cooling circumstances that makes it difficult for melt fills. For incomplete melt fills can cause defects in moulded parts in micro injection moulding which contributes to waste and production costs. Hence, polymers with good flow properties with low viscosity are preferred for micro injection moulding purposes.

2.3. Demoulding force in micro injection moulding

Replicated part will forcibly demoulded or ejected from the replication tool when it reaches stable condition and solidified using a series of injector pins. A sufficient amount of force is needed to overcome the retarding forces that are present at the component and tool interface due to friction and adhesion. Shear stress present from friction and thermally-induced stress due to cooling process can result in a demoulding failure. When a part size reduces or shrinks after cooling process, it reduces the potential sites where the ejector pins can act and this could cause damage to the part when mechanically forced out from tool cores. The shrinkage causes the stress to build up in the cross section of the part [12]. Stresses which are developed from shrinking are really associated to normal force. Therefore, a tangential force is needed to overcome the normal force and create relative motion between the surface part and tool during demoulding process. The component and tool must avoid being overly stressed or damaged during the process to prevent failure on the parts.

2.4. Taguchi method in replication process

Design of experiment is a mathematical and structured method to investigate the influence of many factors simultaneously when there is variation due to controllable and uncontrollable factors. It gives the opportunity to make the best decision scientifically when encountered with the situation that depends on many influencing variables, inputs, factors, and parameters. Taguchi method introduces an experimental technique in the form of design of experiment that is suitable for a wide range of applications. In engineering, the Taguchi method is used for investigating the optimal performance characteristics from a set of factors through design of experiment. It is composed of five basic phases which are mainly planning experiments, designing experiments, conducting experiments, analysing results, and confirming the predicted results [13].

3. Experimental procedure

This section explains the structure of the experimental design and how the experiments were carried out. In micro injection moulding, the selection of test materials is generally determined from a range of polymers according to the application. Every polymer has different properties and shows different results. The test part design is described as it is important for observing the effects of the process parameters considered. Then, the design of experiment with the process parameters considered for this study and the measured response is outlined. The machine used to manufacture the micro injection moulded test parts is presented.

3.1. Test materials

Polymer may be moulded into any shape or structure in conventional injection moulding. However, the restriction of surface area to volume in micro injection moulding only allows those polymers with special properties such as low viscosity and good mechanical strength. The common polymers that are suitable for micro injection moulding are: PMMA, PP, PSU, POM, PE, PA, PEEK, LCP, COC, PBT, and PPE [14]. In this experimentation, TOPAS COC 5013 has been selected to carry out the planned experiment. Topas® is the trade name for Topas Advanced Polymers cyclic olefin copolymers (COC).

3.2. Test part and tool design

The design of a 15 mm x 20 mm x 1 mm microfluidic platform shown in Fig. 1 (a) was used to analyse the effect of process parameters. The features commonly found in microfluidic components in system design include aspects such as reservoirs, channels, and waste compartments. The pin dimensions are 500 µm in diameter and 600 µm in height, and the cross section of the main channels differ between 50 and 200 µm. In addition, the overall design includes a draft angle of 2 to 3 degrees on the side walls.

The tool is manufactured in brass using conventional milling to perform the experiments. The overall size of the mould insert is 25 x 28 x 5 mm with four 3 mm holes for ejectors as shown in Fig. 1 (b). A single open gate design was used to reduce pressure and temperature that could affect the gating. Then, the tool halves were assembled and inspected using a primary mould tool for parallelism before the mating faces were shut off. The part design is made up of many features that could determine the mould accuracy. The influence of the process parameters in replication capabilities could be determined by comparing the dimensions of the tool and mouldings and the part weights.

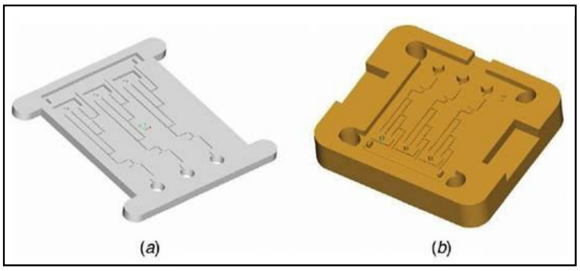

Fig. 1. (a) Microfludic test part design (b) and it's mould insert

3.3. Design of experiment

In this study, four process parameters at two levels given below were employed:

A - Barrel temperature (T_b); Level 1=240, Level 2 = 300
B - Mould temperature (T_m); Level 1 = 70, Level 2 = 130
C - Holding pressure (P_h); Level 1 = Off, Level 2 = On
D - Injection speed (v_i); Level 1 = 200, Level 2 = 800

In order to investigate the level of process parameters that affect the replication process in micro injection moulding process, the demoulding force during the ejection process was focused as the measured response in this experiment. Because this experiment has multi factor effects it will not be easy to study the effects of so many factors since every factor can behave differently at certain point [15]. At the same time, it is essential to know which factors and their interactions are significant for a proper design of experiment. Therefore, it is necessary to use a factorial design to investigate several factors. In this study, the Taguchi method was used to reduce the number of experiments that needs to be conducted without compromising the outcome. Thus, for the four process parameters considered at two levels each a Taguchi L16 Orthogonal Array was selected (see Table 1). Then, the demoulding force was measured as the response for each set of control parameters. The trial was repeated ten times at the same parameter settings in order to measure process variation.

Table 1. The Taguchi L16 Orthogonal Array

	Factors			
	COC			
RUN	T_b [C]	T_m[C]	P_h	V_i [mm/s]
1	240	70	Off	200
2	240	70	Off	800
3	240	70	On	200
4	240	70	On	800
5	240	130	Off	200
6	240	130	Off	800
7	240	130	On	200
8	240	130	On	800
9	300	70	Off	200
10	300	70	Off	800
11	300	70	On	200
12	300	70	On	800
13	300	130	Off	200
14	300	130	Off	800
15	300	130	On	200
16	300	130	On	800

3.4. Experimental machine used

The machine used in this experiment was Battenfeld Microsystem 50 injection moulding machine shown in Fig. 2. This machine is designed as a handling system for the manufacture of micro components. The machine has capabilities of high repeatable process control, accurate dosing of material, and working in clean room environment. An important aspect of this machine is the homogeneous plasticisation at extruder screw that is mounted 45 degrees to the injection axis. In addition, this machine has a precise injection of material into the mould and can achieve injection speeds of 750 mm/s. The experimental results are given in the following section.

Fig. 2. Battenfeld Microsystem 50 injection moulding machine

4. Experimental results and analysis

In studies of influencing factors that affect the replication capabilities in micro injection moulding, the demoulding force was used as a response variable to indicate the output of the process. As discussed before, the demoulding force of micro injection moulding is important as it affects the quality of the moulded part. The experiment was conducted by repeating each run 10 times and the average demoulding force was noted as given in Table 2. The test results were analysed using Signal to Noise (S/N) ratio and ANOVA. S/N ratio is very useful measure for improvement of quality through reduction of noise and improvement of measurement [Ranjit, 2001]. Table 2 presents two different set of results based on the measured responses where S/N ratio is considered to be nominal-the-best and larger-the-better.

Table 2. The Taguchi L16 experimental results

A	B	C	D	S/N ratio nominal-the-best	S/N ratio larger-the-better
1	1	1	1	24.51622	24.26048
1	1	1	2	17.41137	23.77074
1	1	2	1	24.48549	27.50528
1	1	2	2	23.34141	26.92059
1	2	1	1	36.23869	26.4854
1	2	1	2	30.97106	25.67459
1	2	2	1	33.07531	28.01349
1	2	2	2	33.76845	27.10773
2	1	1	1	16.19914	23.4129
2	1	1	2	18.43929	24.2524
2	1	2	1	27.83105	26.88954
2	1	2	2	36.03197	27.6341
2	2	1	1	24.91912	26.42006
2	2	1	2	28.9965	26.93849
2	2	2	1	33.4184	28.17999
2	2	2	2	43.45654	28.60348

The nominal-the-best S/N ratio shown in Table 2 is used to determine the optimal level of process parameters namely, barrel temperature (A), mould temperature (B), holding pressure (C), and injection speed (D) for achieving a target value for the demoulding force in a consistent manner. Hence, the demoulding force achieved at this optimum condition is expected to remain consistently high enough for ejection of moulded parts to achieve a good replication process. The larger-the-better criterion is used to identify the maximum demoulding force and achieve high S/N ratio. The software Minitab 16 was used for analyzing and plotting the results. The results are plotted in Figures 3 and 4 to display the effects of the process parameters upon the demoulding force. The optimum levels for process parameters for nominal-the-best are $A_2B_2C_2D_2$ and for larger-the-better are $A_2B_2C_2D_1$ as indicated in the plots. Both of the set design of experiment is analysed to define the level process parameters from its main factor in micro injection moulding and the confidence level.

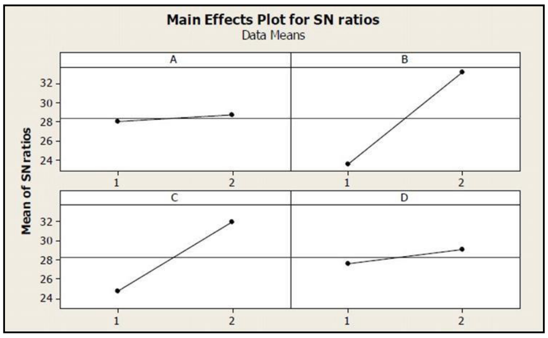

Fig. 3. Main effects plot for S/N ratio at nominal-the –best

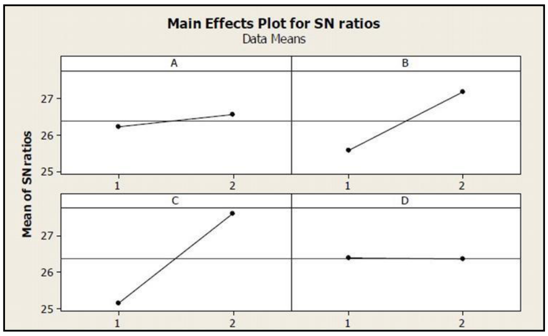

Fig. 4. Main effects plot for S/N ratio at larger-the –better

The main effect graphs also show the significance of process parameters. The steeper the line the more significant and the graphs show the parameters C and B i.e. holding pressure (P_h) and mould temperature (T_m) are both significant while A and D i.e. barrel temperature (T_b) and injection speed (v_i) are less significant. For nominal-the best the barrel temperature (T_b) is least significant while for larger-the-better it is the injection speed (v_i).

Generally, both graphs show that the parameter B i.e. mould temperature (T_m) must be set at high level in order to fill into the micro cavities more efficiently due to viscosity of the melt polymer. From the nominal-the-best analysis, the mould temperature (T_m) played a main role for contribution in achieving optimum level for demoulding force. Thus, it can improve the replication process by keeping the heat to prevent fast cooling in micro cavities. In other words, the cooled layer of melt fills eventually can block the micro cavities. However, the larger-the-better showed that holding pressure (P_h) is most significant due to the fact that the melt fills can be solidified completely before the moulded parts could be ejected. Holding pressure time starts from the injection of melt fills and prevents the melt fills from overflow. The duration of the holding pressure gives sufficient time for melt fills to be frozen in micro cavities of the mould before the melt is cooled completely.

In Taguchi analysis the calculations made by focusing on the values of S/N ratio to determine the level setting of process parameters has shown some interesting and positive results. In general, the larger value for S/N ratio is better for the output results since this measure will ensure that the external factors that can influence the replication process is kept minimal so that the replication capabilities are increased The nominal-the-best criterion will enable the process to achieve and maintain a recommended amount of demoulding force necessary for an optimum production of replication process. Meanwhile, the larger-the-better is most appropriate for high surface quality and mass production.

The interaction between the process parameters are plotted in Figures 5 and 6. The interactions between the parameters indicate if adverse effects are caused by increasing or decreasing one parameter upon the measured response. Parallel lines in the plot shows no interactions while intersecting lines show the presence of interaction.

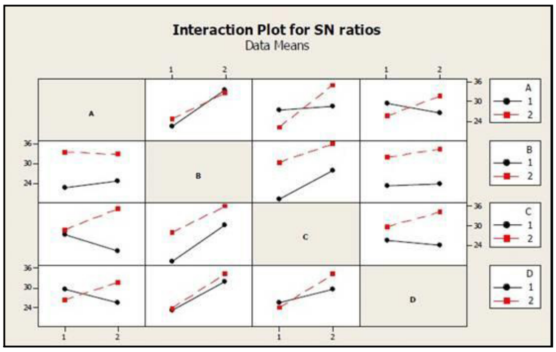

Fig. 5. Interaction plot for S/N ratio at nominal-the –best

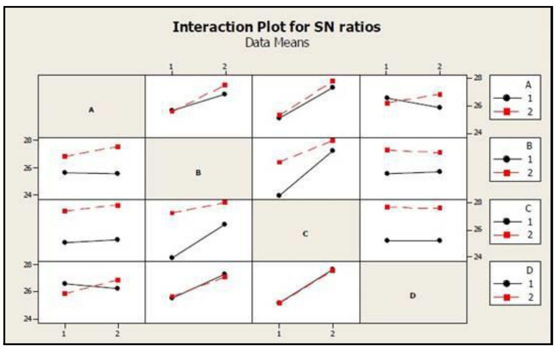

Fig. 6. Interaction plot for S/N ratio at larger-the –better

For nominal-the-best, Fig. 3 shows some interaction between A and C and A and D. The results are optimum when the parameters are at level 2. For larger-the-better, Fig. 4 shows some interaction between B and C and A and D. The results are optimum when the parameters are at level 2.

The interaction of the main process parameters such as barallel and mould temperatures are important in micro injection moulding for producing high quality moulded parts with accurate dimensions.

The interaction between A and C prove that the barrel temperature and holding pressure affect the solidification of moulded parts. The interaction of A and D shows that the melt fills in the micro cavity is significant.

5. Conclusion and future work

Design of experiment using Taguchi L16 Orthogonal Array has been conducted with four process parameters namely, mould temperature, barrel temperature, holding pressure, and injection speed in order to understand the effect of these parameters during the micro injection moulding process. Using the L16 Orthogonal Array experiments have been carried out to produce test parts and obtain the demoulding force as the measured response. Each trial was repeated ten times and average values were used in the analysis of the results. The analysis was carried out using Minitab16. Two criteria for S/N were used The results obtained showed that for nominal-the best an optimum setting level of process parameters were $A_2B_2C_2D_2$ and for bigger-the-better the optimum setting level of process parameters were $A_2B_2C_2D_1$. The study also showed some interaction between parameters A and C, A and D, and B and C. This study has shown that the most significant parameters are mould temperature and holding pressure. Different polymers will be used in the future to study the effects of these process parameters upon different materials.

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