A Study on the Effects of Process Parameters on Swirl Marks of Microcellular Injection Molded PC Parts

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ABSTRACT

The effects of processing parameters on surface roughness of microcellular injection molded PC parts were investigated. Taguchi design of experiments (DOE) was performed with varying mold temperature, melt temperature, injection rate and supercritical fluid (SCF) concentration. It was found that mold temperature, injection rate and melt temperature appear to be the predominant molding parameters which affect the surface roughness. The results are helpful for designers to optimize the process conditions to achieve high quality microcellular PC part.

KEYWORDS: *Microcellular injection molding, Surface roughness, Process conditions, Taguchi DOE*

1. INTRODUCTION

Microcellular injection molding mixes supercritical fluid with a polymer melt to produce a single phase polymer/gas solution and then a sudden large pressure drop triggers the thermodynamic instability of the solution, resulting in numerous nucleation sites where cells grow. This process produces parts with a microcellular structure using lower injection pressure and short cycle time while elimination the need for a packing stage and improving the dimensional stability of the molded parts. Commercial interests in microcellular parts continue to increase because of their lightweight and excellent properties.

However, the surface defects on the microcellular parts limit microcellular injection molding technology to applications involving interior products. The widely observed swirl marks affect both part clarity and aesthetics and restricts the superior properties of the microcellular parts. Cha and Yoon et al. [1] attributed the swirl marks to the rupture of macroscopic bubble, which were sheared on

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J. Polym. Mater. Vol. **35,** No. 3, 2018, 257-264

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DOI : https://doi.org/10.32381/JPM.2018.35.03.1

the cavity wall during the injection process. The escaped gas was trapped between the polymer melt and the mold surface as the melt begins to solidify. Many efforts have been devoted to the elimination of swirl marks. Inserting a thermally insulated composite polymer film onto the mold wall might help keeping the mold surface temperature high, which will be beneficial to expel the wrapped gas out to improve the surface quality [2, 3]. Variable mold temperature technique [4] was also proposed to increase the mold surface temperature to decrease surface roughness of microcellular parts.

Another method to improve the surface quality of microcellular part was the co-injection molding process [5]. Prior to the injection of a foaming core material, a solid skin material was injected. The surface quality of the produced part was similar to that of a conventionally molded component. A gas counter pressure process [6] was also employed to produce part with improved surface quality. In this process, a high-pressure gas was used to suppress cell nucleation. Bubbles began to form when the counter high-pressure gas was released toward the end of the injection, thus a solidified skin without gas was achieved and swirl marks were eliminated.

Though these method was useful to improve the part surface quality, there exist many difficulties in apply them in industries because the production costs increase greatly when using these methods. Lee and Turng et al. [7] employed appropriate material formulation and gas concentration to control the cell nucleation rate to obtain parts without swirl marks. Though the proposed novel method has the advantage that no additional equipment was required, smaller and denser cell morphology was not easy to achieve. Therefore, a clear understanding of the mechanisms responsible for surface defects of microcellular injection molded part remains meaningful and challenging [8, 9]. Hu and Hu [10], Li and Hu et al. [11] pointed out that critical bubble breakup sizes were found to be positively correlated with the surface roughness, and controlling the bubble critical breakup sizes could be an efficient way to reduce the surface roughness.

In this study, the Taguchi design of experiment (DOE) was employed to study the effects of process conditions on the occurrence of swirl marks on microcellular PC parts. Mold temperature, melt temperature, injection rate and gas concentration were considered. The swirl marks were characterized by roughness measuring instruments. The results are useful to clarify the mechanism for swirl marks formation and helpful for designers to adjust process conditions to obtain satisfied parts.

2. Taguchi DOE

Taguchi method is a powerful yet simple tool. It is used for designing experiments to investigate the relationship between process parameters and performance characteristic that defines how well the process is functioning. It emphasizes a mean performance characteristic value close to the target value rather than a value within certain specification limits, thus improving the product quality.

The Taguchi method allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experiment, thus saving time and resources. Orthogonal arrays are employed to organize the parameters affecting the process and the levels at which they should vary. This method is straightforward and easy to apply. The general steps are described as follows:

a. Define the process objective, or more specifically, a target value for a performance measure of the process. For example, the goal may be to minimize the surface roughness. The deviation in the performance characteristic from the target value is used to define the loss function for the process.

b. Determine the design parameters affecting the process. Parameters are variables that affect the performance measure such as temperatures, pressures, etc. that can be easily controlled. The levels of these parameters must be specified.

c. Create orthogonal arrays for the parameter design. The selection of orthogonal arrays is based on the number and level of each parameter.

d. Conduct the experiments indicated in the completed array, and analyze data to determine the effect of process parameters on the performance measure.

The Taguchi method tests pairs of combinations instead of evaluating all possible combinations, thus it allows for the analysis of many different parameters without a prohibitively high amount of experiments and can be used to quickly narrow down the scope of a research project or to identify problems in a manufacturing process. For example, a process with 8 variables, each with 3 states, would require 6561 (3^8) experiments to test all variables. However, using Taguchi's orthogonal arrays, only 18 experiments are necessary, or less than 0.3% of the original number of experiments. In this way, it allows for the identification of key parameters that have the most significant effect on the performance characteristic value so that further experiments on these parameters can be performed and the parameters that have little effect can be ignored.

3. EXPERIMENT & DISCUSSION

A rectangular PC part (Figure 1) with dimensions of 100mm (length) × 100mm (width) × 2 mm (thickness) was designed for the experiments. An Arburg 570S Allrounder 2200-800 injection molding machine (Arburg, Germany) was used for microcellular injection molding experiments. The supercritical fluid supply system used in this study was the S11-T200 model (Trexel, Wilmington, MA, USA). The machine (Figure 2) consists of Nitrogen supply, a SCF metering and control system, and a specialized plasticizing unit including positive screw control and a shut off nozzle. The material used in this study was an injection molding grade transparent PC resin (HF 1130R, GE). It has a melt index of 25g/10min, and a specific gravity of 1.2. Its injection molding parameters were: melt temperature 280 - 300°C, mold temperature 60 - 80°C. Commercial grade nitrogen, which is more commonly used in microcellular injection molding than CO_2, was used as the physical blowing agent for the microcellular injection molding trials.

The surface roughness was used as an indicator of swirl marks. To analyze the surface roughness of the molded part, Surfan Alyzer 4000 was employed. Using this instrument, the surface roughness which was expressed as (Ra) can be calculated with the amplified signal generated by an iron needles moving on the part surface. (Ra) is the arithmetic mean of deviations from the mean line. The iron needles moved 15mm along flow direction on the part surface. The surface roughness were evaluated at nine different positions as shown in Figure 1 and the average surface roughness based on measurement done at all nine

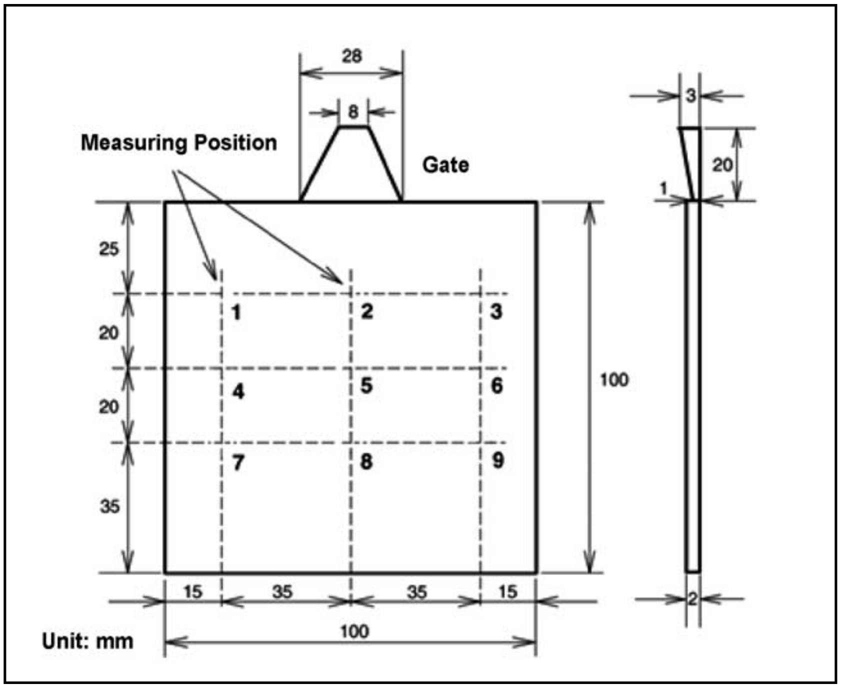

Fig. 1. Schematic diagram of the part dimensions

TABLE 1. Levels of orthogonal experiment process parameters

factor / level	Melt temperature A/ºC	Mold temperature B/ºC	Injection rate C/cm^3/s	Gas concentration D /wt%
Level 1	280	60	80	0.30
Level 2	290	70	90	0.35
Level 3	300	80	100	0.40

locations was recorded. For each processing condition, five specimens and nine points on each specimen were tested. The average surface roughness value of the five samples was used for analysis.

The design of experiments via Taguchi method was employed to indentify the effect of molding parameters on the swirl marks. Molding parameters such as melt temperature, mold temperature, injection rate and gas concentration were considered here. The levels these parameters should be varied at must be determined, which requires an in-depth understanding of the process, including the minimum, maximum, and current value of the parameter. For example, if the temperature could be varied between 60°C and 80°C and it was known that the current operating temperature was 70°C, three levels might be chosen at 60°C, 70°C, and 80°C. Also, the cost of conducting experiments must be considered when determining the number of levels of a parameter to include in the experimental design. In this study, molding parameters were varied at three levels.

Knowing the number of parameters and the number of levels, the proper orthogonal array could be selected. To facilitate the analysis of the experimental results, a fractional three-factorial, three-level, L9 Taguchi design was conducted in this study. The predefined array was created using an algorithm Taguchi developed, and allows for each variable and setting to be tested equally. Interactions between these factors were not considered. The molding conditions and levels and their corresponding experiment values were shown in Table 1 and Table 2 respectively. For each trial in the L9 experiment, five samples were collected.

To determine the quality characteristics and to optimize the microcellular molding process, the signal-to-noise (S/N) ratio analysis was performed to encapsulate the effect of environmental conditions from unit to unit on those parameters that can be controlled. An improvement in the part surface quality was indicated by an increase in the signal-to-noise ratio. For better surface quality, the smaller-the-better characteristics were looked for. With the smaller the better formulation, the signal-to-noise ratio increased as the surface roughness decreased. The smaller-the-better signal-to-noise formation was expressed as:

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{\,2}\right) \tag{1}$$

where η was signal-to-noise ratio, Y_i was the i^{th} experiment result and n was the number of experiment. Here it should be pointed out that in the analyses below the surface roughness was determined by averaging over nine different positions as shown in Figure 1. The averaged surface roughness for all the L9 trials were listed in Table 2.

TABLE 2. The orthogonal experiment table

Trial No.	Level of factor				Surface roughness/μm	S/N
	A	B	C	D		
1	1	1	1	1	3.178	-10.0451
2	1	2	2	2	1.680	-4.63738
3	1	3	3	3	1.326	-2.54185
4	2	1	2	3	2.654	-8.52069
5	2	2	3	1	2.576	-8.49478
6	2	3	1	2	2.534	-8.16563
7	3	1	3	2	2.502	-8.04708
8	3	2	1	3	2.460	-7.86641
9	3	3	2	1	1.852	-5.3622

The analysis of variance could be used to quantitatively estimate the relative contribution of each factor to the overall measured response. Based on analysis of variance, the main effects of variables on the roughness were calculated, and the optimal combination of variables and the corresponding results for the quality objective were predicted. By averaging the signal-to-noise ratio for each parameter level, the signal-to-noise ratio response table was generated and the effect of a parameter or the rank of a factor could be signified by the difference between the averaged signal-to-noise ratio values. The variations of the signal-to-noise ratio for surface roughness index were shown in Table 2.

TABLE 3. Variations of the S/N ratio

Level	A	B	C	D
1	-5.7414	-8.8710	-8.6924	-7.9674
2	-8.3937	-6.9995	-6.1734	-6.9501
3	-7.0919	-5.3566	-8.3456	-6.3096

From Table 3, it can be seen that the optimum factor levels that could statistically result in the minimum roughness were $A_1B_3C_2D_3$. That is to say, the recommended optimal molding conditions for the surface roughness were: melt temperature 280ºC, mold temperature 80ºC, injection rate 90 cm^3/s, and supercritical fluid content 0.4%. However, the optimum combination of factor level was not included in the main experiments and thus a new experiment with the corresponding process conditions was done. The surface visual quality molded under different conditions was shown in Figure 2. The measured surface roughness for the optimized parts was 1.210, which was lower than all the surface roughness shown in Table 2.

The effect of various factors on a product's swirl marks was important for designers to determine molding conditions. The effect was the ratio of the sum of squares caused by the factor to the total sum the squares. The sum of squares caused by various factors was calculated by:

$$SSSF = 3\left(m_{f_1} - m\right)^2 + 3\left(m_{f2} - m\right)^2 + 3\left(m_{f3} - m\right)^2 \quad (2)$$

where, $m_{f_i} = \frac{1}{N}\sum_i \eta_{fi}$, f is factor, i is level, m_{fi} is the average value of factor f with level i, N is number of experiment, m is the average of all the S/N ratio, and η_{fi} is the signal-to-noise ratio value corresponding to level i of factor f. The effect of various factors on cell size was shown in Table 4.

From Table 4, the molding parameters that affect the surface roughness of microcellular injection molded PC part were, in order of their influences, mold temperature, injection rate, melt temperature, and supercritical fluid concentration, with the last parameter being much less influencing than the first three ones.

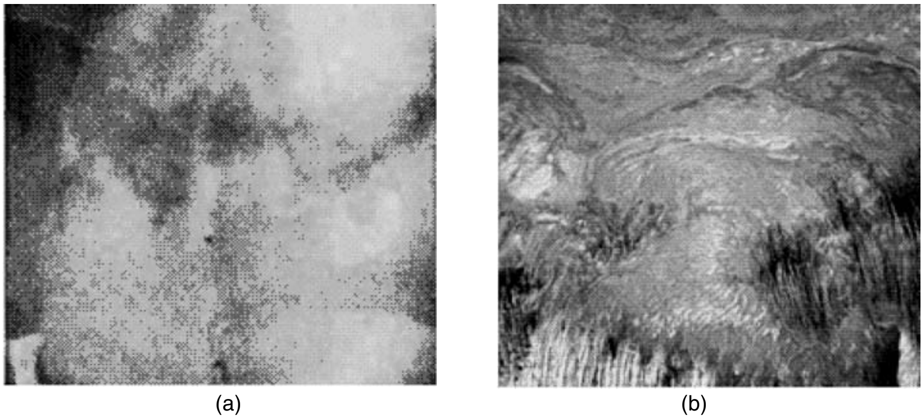
(a) (b)

Fig. 2. Surface quality for parts molded under (a) optimized conditions (b) trial No. 1

TABLE 4. Effects of factors on surface roughness

Factor	Degree of freedom	Sum of squares	Effect on roughness/%
A	2	10.5529	21.79
B	2	18.5526	38.32
C	2	15.1211	31.23
D	2	4.1931	8.66

Through the analysis, it was easy to draw a conclusion that mold temperature, injection rate and melt temperature were the main factors which affect the surface roughness of samples and the supercritical fluid concentration was secondary one. With the increasing of melt temperature, mold temperature and injection rate and the reducing of the supercritical fluid concentration, the surface quality of molded PC parts could be improved. This was because that swirl marks were caused by the gas trapped at the polymer/mold interface as the plastic/gas solution began to solidify. Increasing the mold temperature and melt temperature could delay the solidification of the melt, which would be helpful to discharge the trapped gas. If a plastic/gas solution did not solidify when it contacted the mold surface, any escaped gas would be forced to flow to the cavity end and then out through the gas vent, thus removing any swirl marks. As a result, microcellular foamed plastics, which had glossy and swirl-free surfaces, could be produced. Increasing injection rate would reduce cooling effects and enhance shear flow, thus increasing the melt temperature as a result. In addition, increasing injection rate would shorten the time for bubble to grow and produced small-sized bubbles, which in favor of less gas being trapped on the mold surface and a better surface quality. However, increasing the concentration of the supercritical fluid would increase the number of micro bubble in the melt, and thus led to more escaped gas and worse part quality.

4. CONCLUSIONS

Microcellular injection molding presents a new research area with numerous potential applications. The effects of molding conditions on the surface roughness of microcellular injection molded PC parts have been studied using efficient Taguchi DOE tool. It was found that the relative significance of molding parameters affecting surface roughness was given in a descending order as: mold temperature, injection rate, melt temperature, and supercritical fluid concentration. The recommended optimal molding conditions were: melt temperature 280ºC, mold temperature 80ºC, injection rate 90 cm^3/s, and supercritical fluid content 0.4%. The conclusion can be used by process designers to set up molding conditions to achieve high quality PC part.

5. Acknowledgements

The project presented in this paper was supported by the NSFC Henan Joint Foundation for Fostering Talents (U1304107). The authors would like to acknowledge the sponsors.

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Received: 10-04-2018

Accepted: 29-08-2018