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OPTIMIZATION OF THE MICRO MOLDING OF A BICONCAVE STRUCTURE

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ABSTRACT

Micro molding is a rapid and cost-effective micro manufacturing technology. However, during the manufacturing process, different kinds of products usually face problems with uneven thicknesses or particular structure designs, resulting in uneven products shrinkage. This research focuses on exploring the problems of molding a micro part with biconcave structure and sharp edges. Using the Taguchi Experimental Method, it aims to find the critical molding parameters which influence the moldability of the micro part, as well as to minimize the shrinking of part. This study used polypropylene (PP) for the injection molding and successfully resolved the void defect which appeared in the center of this biconcave structure. Melt temperature contributed the highest percentage (41.235%) to the shrinkage, followed by injection speed (31.947%) and mold temperature (12.887%). The optimal process parameters for injection molding obtained from the experiment which are melt temperature 240°C mold temperature 90°C, and injection speed of 30 mm/s and the shrinkage rate is 1.641%.

Keywords: Biconcave structure; Injection molding; Sharp edges; Shrinkage

1. INTRODUCTION

The development of technology and science has progressed rapidly, as can be seen in the development of computer hardware products, digital cameras, mobile phones and other electronic goods. Many electronic devices are made as thin and small as possible, which contributes to their popularity. Consequently, this poses some difficulties for manufacturers to achieve such small sizes with high levels of accuracy if they still apply traditional manufacturing processes.

One example of a small electronic devices is the LED (Light emitting diode). A plastic lens is usually mounted on the LED chip to obtain the desired light distribution patterns. Chen et al. (2011) and our own lab (Molding Technology Synergy Lab./Kaohsiung) have developed a LED lens with biconcave structure (Figure 1), giving both high luminous uniformity (93.35%) and high viewing angle (135°).

One of the popular technologies for making plastic lenses is injection molding. This manufacturing method has advantages over other processes, in that it can mass produce parts rapidly and effectively (Hasnan et al., 2017). In recent years, injection molding technology has evolved to micro-injection molding, which can produce parts with small volume and

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microfeatures with high precision and at low cost. The appearance, weight, and size of the machines are evidence of the difference between conventional injection molding and micro-injection molding machines. From their appearance, conventional injection machine are more prominent than a micro injection ones, but typically micro-injection machines require higher stability and controllability to make high precision micro parts.

The Taguchi method is a popular method used in the molding industry to obtain the best part quality. It simply uses the response table and graph from the experiment data to be analyzed, and then directly finds the combination of levels that gives the optimal response (Hadiyat & Wahyudi, 2013; Pavani et al., 2017). The parameter design is an optimized part of the Taguchi method and is often used to improve the product and process design. Its intention is to find a set of optimal parameter level combinations, so that the average target value can be reached with smallest variance, which means that the loss of the quality characteristic is minimized.

The micro-injection technique has recently been used, especially for making small plastic parts with high precision requirement. In addition to the Taguchi experimental method, Lin et al., (2004) worked on a plastic micro-injection part technique to manufacture high aspect-ratio optical fiber ferrules. They used Taguchi's design experiment to evaluate the effect of parameters on the final properties, finding that mold temperature, holding pressure, and holding time could improve the alignment accuracy and lifetime of the microcore pin and minimize volumetric shrinkage. This new concept can be applied in the molding of microtubes. Pal et al. (2012) studied the micro-injection molding process of polypropylene dog bone shaped bars using Taguchi method; the results of their research showed the key micro-injection molding process parameters were injection pressure, holding time, and melt temperature. Lee and Lin (2013) selected melt temperature, mold temperature, packing pressure, holding time and cooling time as control factors, then employed the Taguchi method and finite element analysis to explore the LED lens molding and to find the relationship between shrinkage and the injection molding process parameters. Their results show that the effect of melt temperature on the shrinking of the LED lens has the most significant contribution, while cooling time made the smallest contribution. Skrlec and Klemenc, (2016) show that micro-injection molding parts quality are influenced by processing parameters such as injection speed, holding pressure, holding time, injection pressure, mold temperature, and melt temperature. Jiang et al. (2018) investigated the relationship between the morphlogical evolution and mechanical properties of PC/PET blends prepared by micro injection molding by applying Taguchi method; their results showed that the molecular of PC/PET first increases, then decreases in line with increased injection speed. Masato et al. (2018) used micro injection molding to produce medical and aerospace parts, and also applied Taguchi experiment on their study. They selected injection speed, melt and mold temperature, and holding pressure as the main processing parameters and found that the mold temperature and injection speed are the most effective parameters in the improvement in the dimension and the quality of molded part.

Computer-aided-engineering is a time saving tool for both molding part design and mold design. Marhöfer et al. (2013) employed Moldflow injection molding simulation software in micro-injection molding in order to obtain the optimum injection molding process parameter combination before doing the actual micro-injection molding process. Wang et al. (2018) employed Moldex3D in the micro injection molding to produce Blu-ray pick up lens in order to establish the optimum injection molding process co mbination. They demonstrated the possibility of using mold filling simulation software assisted in micro molding.

Chen et al. (2011) and our own lab have integrated optical simulation software and neural networks to design biconcave structured LED lens, but have not actually made such as a lens. It has non-uniform thickness distribution and with sharp edges that could causes defects in the molding process. The aim of this research is to study the moldability of this lens structure. Moldex3d molding simulation software will be implemented in the mold design and the Taguchi Method will also be applied to investigate the effects of molding parameters on the part's quality, and furtherly to find the optimal parameter combination for micro injection molding of the part.

2. METHODS

The object of this study is the biconcave spherical structure LED lens as shown in Figure 1. The thickness of this part is not uniform and there is a sharp edge on the top. Short-shots, sink marks, and other defects usually occur when molding micro parts with sharp edges and non-uniform thickness. This study explores the molding parameters effects on the molding quality of this biconcave spherical structure. The material used for molding lenses are usually PC or PMMA, which have suitable properties such as stiffness, rigidity, and optically transparency. However, polypropylene (PP) TAIRIP K1011 was used as the material in this study.

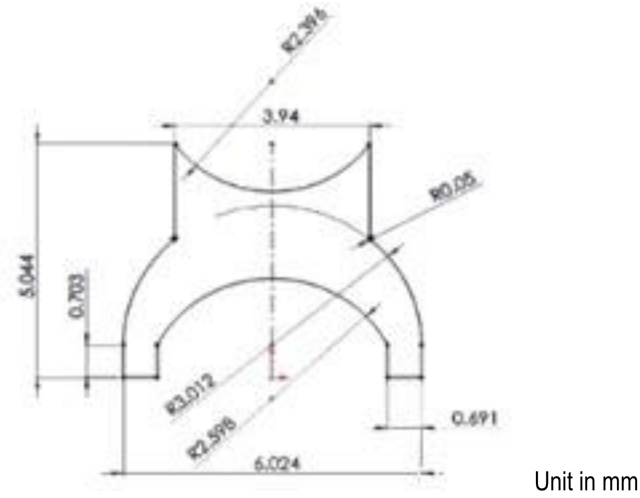


Figure 1 Biconcave spherical LED lens

2.1. Mold System Design

The design of the biconcave spherical structure used in this study was based on the lens designed by Chen et al. (2011). To prevent deterioration of the optical quality, the mold did not have the draft angle, because the part is too small. The mold cavity for making this lens is shown in Figure 1. The Battenfeld Microsystems 50 was used for this micro-injection molding. This machine is specially designed and optimized for micro parts of less than 1 cm^3 in volume and has high precision. The design of the mold and processing parameters are the controlling factors to provide the desired shape in the molded part (Sedighi et al., 2017). The cavity, gate, runner, and sprue were designed for this Microsystem 50, as shown in Figure 2.

The volume ratio of the feed system (152.899 mm^3) to the part (56.434 mm^3) is 2.7, which is much lower than that of the same part molded with the traditional molding machine. A general guide is that the gate should be located in the thickest section of the part if possible. For this biconcave spherical part, the mid-section is the thickest and the gate should be here, but it would leave a mark after demolding and would eventually be detrimental to lens optical quality as its original designed. A side gate was therefore selected, located at the bottom of the side of the part, being a square shape with a length of 1 mm, width of 1 mm and thickness of 0.4 mm, as shown in Figure 2.

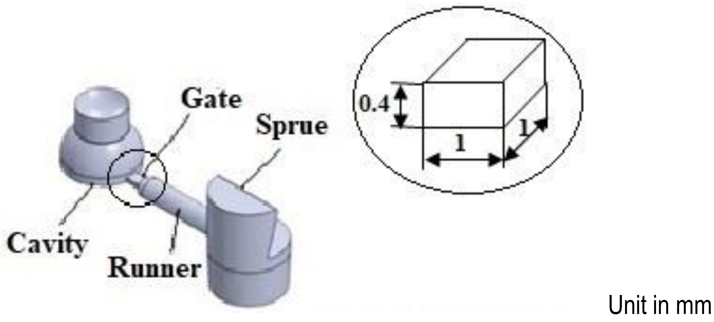


Figure 2 Design mold of the biconcave spherical structure

2.2. Molding Parameters and Material Properties

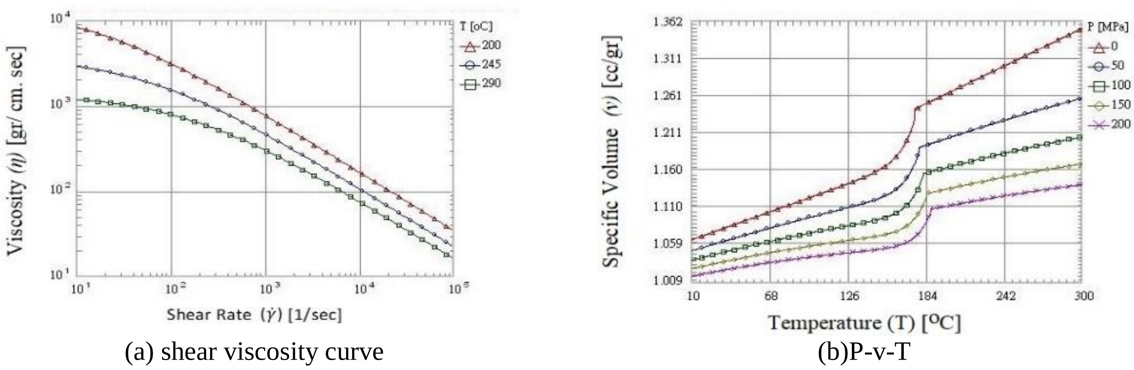
The viscosity of the plastics plays an essential role in the filling of the microstructures in micro parts. However, with lower viscosity it is more natural for the melt to flow into microstructures, which tends to give better replication of the cavity contour. Shear viscosity is dependent on the melt temperature and shear rate during the filling process. The relation between the shear viscosity of the polymer, temperature, and shear rate can be described by Cross and Carreau (Helleloid, 2001) Equations 1 and 2;

$$\eta = \frac{\eta_o}{1 + \left(\frac{\eta_o}{\tau^*}\dot{\gamma}\right)^{1-n}} \tag{1}$$

where η is the viscosity, ηo is the zero-shear viscosity, τ^* is the critical shear stress, n is the power-law index, and $\dot{\gamma}$ is the shear rate.

$$\eta_o\,(T) = D_1.\exp\left[\frac{A_1(T - D_2)}{A_2 + T_1 - D_2}\right] \tag{2}$$

where T is the melt temperature, D_1 is the viscosity at a reference temperature, and D_2, A_1 and A_2 are constants describe the temperature dependency. Figure 3a shows the shear viscosity curve of this material, while Figure 3b shows the pressure-specific volume-temperature properties. Table 1 shows other thermal related properties for this PP TAIRIPRO K1011.



(a) shear viscosity curve (b)P-v-T

Figure 3 Shear viscosity and P-v-T of TAIRIPRO K1011

Table 1 Thermal Properties of TAIRIPRO K1011

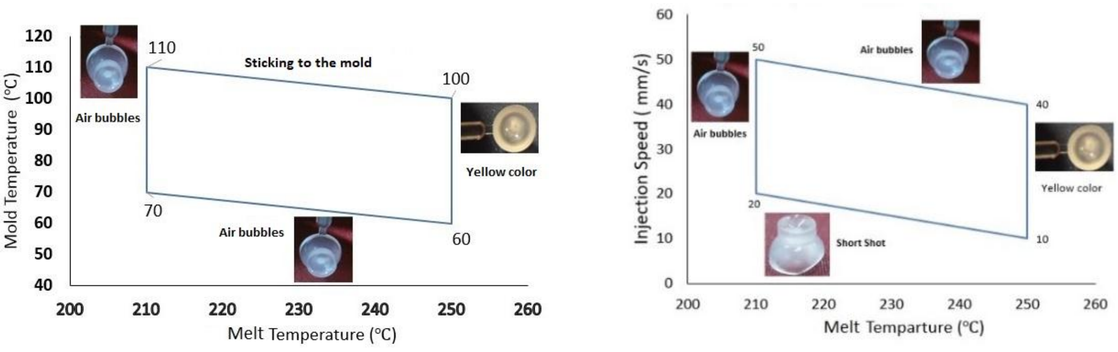
Properties	Value
Melt Temperature (T_{melt})	200℃-290℃
Mold Temperature (T_{mold})	30℃-50℃
Ejection Temperature	90℃
Heat Deflection Temperature	110℃
Linear Shrinkage	1.4%-1.8%
Thermal Conductivity (@23℃)	2.1 cal/sec/cm/℃
Specific Heat (@23℃)	0.46 cal/g/℃
Density (η) (@23℃)	900 kg/m³

Although higher melt temperature will reduce the melt viscosity, it might cause higher part shrinkage after cooling. Filling at higher injection speed (higher shear rate) could lead to higher shear stress, resulting in high residual stress and warpage. Besides melt temperature and shear rate, another critical factor that influences the molding quality is mold temperature. Higher mold temperature would reduce the rapid formation of frozen skin layers, meaning the melt will have a better chance to fill the microstructure. However, such higher temperatures could also cause higher part shrinkage, especially in crystalline polymers.

The Taguchi experimental method is a simple and time-saving approach to finding the group of parameters that produces better molding qualities. Therefore, this method was implemented to find the effects of molding parameters on the micro part quality. The control parameters considered in this experiment were injection speed, melt temperature, and mold temperature. Battenfeld Microsystem 50 micro molding machine was used to run the molding experiments.

2.3. Processing Window

In the Taguchi experiment, the parameters should be kept inside the window to at least produce visually acceptable parts. A series of experimental runs was conducted to determine the processing window for the three control parameters. The results from the trial experiments indicate that when the injection speed is less than 20 mm/sec, the melt was not able to completely fill the cavity, resulting in a short shot defect. The part became yellowish when the melt temperature was higher than 250°C. Voids can be found in the thick area of the parts when the injection speed is higher than 50 mm/sec, as well as when the melt temperature was less than 210°C. As for the mold temperature, voids appeared when this was less than 70°C, and the melt was unable to solidify completely as the cooling rate was relatively low when the mold temperature was higher than 90°C, causing the part to stick to the mold and not be successfully demolded from it. The results shown in Figures 4a and 4b indicate that the appropriate melt temperature should be in 210°C to 250°C.



(a) (b)

Figure 4 Processing window: (a) Mold temperature vs. Melt temperature; (b) Injection speed vs. Melt temperature

2.4. Taguchi Experiment

In this Taguchi experiment, the selected control factors were melt temperature, mold temperature, and injection speed. According to the processing windows found in the trial experiments, the ranges of the parameters were set as melt temperature (MT) 220°C –240°C, mold temperature (MoT) 70°C–90°C, and injection speed (IS) 20 mm/s–40 mm/s. Each of the parameter ranges had three levels, as listed in Table 2. Other molding parameters kept fixed in the Taguchi experiment are listed in Table 3.

Table 2 Control factor levels

Level	MT(℃)	MoT(℃)	IS(mm/s)
1	220	70	20
2	230	80	30
3	240	90	40

Table 3 Fixed molding parameters

Fixed forming parameters	Value
Metering volume	295 mm^3
Screw rotation speed	50 mm/s
Back pressure	30 Bar
Packing speed	0.1 mm/s
Packing time	3 s

The primary aim of this experiment was to observe the feasibility of molding the biconcave spherical structure part with a substantial difference in the thickness ratio and sharp edge, and to find the effects of the molding parameters on the molding quality. The finished parts should be defect-free, and the dimensions should be close to the original design. Molded part shrinkage was selected as a quality index for this Taguchi experiment.

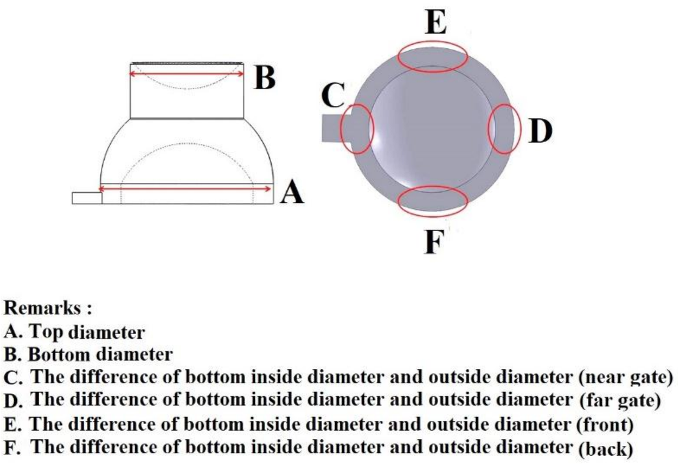


Figure 5 The measurement area of the biconcave spherical structure

After molding, the parts were rested for 24 hours before measurement of the dimension. Three parts for each experimental run were selected and measured. Dimensions at six different locations of the part, as shown in Figure 5, were measured. The linear shrinkage L_S of each dimension can be calculated by:

$$L_s = \left[\frac{Mold_{Size} - Part_{Size}}{Mold_{Size}}\right].100\% \quad (3)$$

where $Mold_{size}$ is the designed dimension and $Part_{Size}$ is the dimension measured from the molded part. The $Mold_{size}$ dimensions to be measured are shown in Figure 5, where A is 1.960 mm, B is 3.015 mm, C is 0.7 mm, D is 0.7 mm, E is 0.7 mm, and F is 0.7 mm. Each part has six linear shrinkage numbers, and the averaged of these represents the linear shrinkage of the part; for each experimental run, there were three averaged linear shrinkages, y_1, y_2, and y_3. In an experimental run, each dimension had three shrinkage numbers, and the standard deviation of that could be calculated. For example, s_A is for mold dimension A, s_B is for mold dimension B, etc.

The averaged linear shrinkage of the measurements and their deviations were calculated, representing the quality of the part (y). The part was expected to shrink as little as possible with small deviation, meaning it is a smaller-the-better experiment. The S/N ratio of the smaller-the-better characteristic was calculated using Equation 4:

$$\eta = -\log(y^2 + s^2) \quad (4)$$

where $y^2 = (y_1^2+y_2^2+y_3^2)/3$ and $s^2 = (s_A^2+s_B^2+s_C^2+s_D^2+s_E^2+s_F^2)/6$.

3. RESULTS AND DISCUSSION

3.1. The Taguchi Method Experiment

The shrinkage and the standard deviation of the nine runs are listed in Table 4, together with the calculated S/N. The results indicated that the ninth run demonstrated the best performance.

Table 4 Results of the sum average of shrinkage, the sum of the standard deviation, and the S/N ratio

No	MT	MoT	IS	Part Shrinkage (%)			Ave.	y^2	s^2	y^2+s^2	S/N
				y_1	y_2	y_3	y	(10^{-4})	(10^{-4})	(10^{-4})	ratio
1	220	70	20	2.448	2.898	2.535	2.627	6.940	1.441	8.381	30.767
2	220	80	30	2.622	2.613	2.115	2.450	6.059	1.098	7.156	31.453
3	220	90	40	3.210	2.212	2.648	2.690	7.403	0.927	8.330	30.794
4	230	70	30	2.835	2.558	2.855	2.749	7.578	1.280	8.858	30.527
5	230	80	40	3.058	3.058	2.830	2.982	8.905	0.990	9.895	30.046
6	230	90	20	2.260	3.465	3.102	2.942	8.911	1.279	9.119	29.918
7	240	70	40	2.847	3.568	2.693	3.036	6.946	1.118	8.921	30.935
8	240	80	20	2.692	2.165	2.832	2.563	6.650	0.884	6.314	31.230
9	240	90	30	1.708	1.693	1.520	1.641	2.699	0.463	4.108	35.001

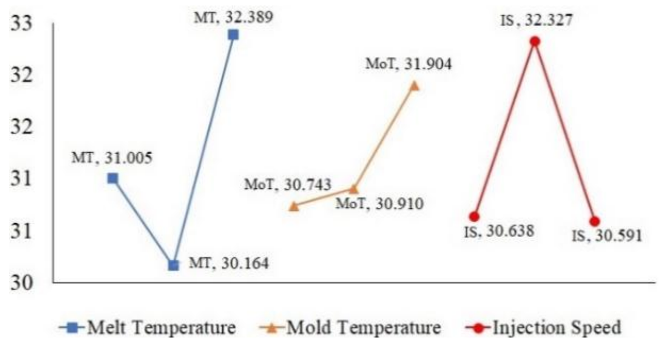


Figure 6 Factor response S/N graph

From the factor response chart shown in Figure 6, the best factor combination is MT3 (240°C), MoT3 (90°C), and IS2 (30 mm/s), as employed in the ninth experimental run. The average shrinkage of the part is 1.641% which is close to the mold shrinkage 1.6% measured by the material supplier.

The contributions of the factors are melt temperature at 41.235%, injection speed at 31.947% and mold temperature at 12.887% as shown in Table 5.

Table 5 Variance analysis

Factors	Change (SS)	Degrees of freedom (f)	Variation (V)	Pure chance (S')	Contribution (%)
Melt Temperature	7.573	2	3.787	7.573	41.235
Mold Temperature	2.367	2	1.183	2.367	12.887
Injection Speed	5.867	2	2.934	5.867	31.947
error	2.554	-	-	-	8.518
Total (St)	18.366	6	3.061	18.366	100.000

Melt temperature is the dominant factor in the molding of this biconcave micro part. Although at higher melt temperature the molding part tends to shrink more, the viscosity of the melt is lower, and the melt more comfortably fills the microstructure, as well as there being more chance for the injection plunger to push melt to the cavity to compensate the material shrinking during packing stage. Higher injection speed helps to reduce the melt viscosity, and the dissipation heating causes melt to heat up, further reducing the melt viscosity, but also causing higher shear stress, leading to greater distortion in part. A higher mold temperature usually results in higher shrinkage of the part; however, at such a temperature the formation of solidified skin is slow, quickly for the melt to fill in microstructure and also providing more time for the material to enter the cavity during the packing process. We can see that high melt and high mold temperatures are essential for molding micro parts with sharp edges

3.2. Processing Window Experiment

Short-shot experiments were conducted by adjusting the filling volume in both molding with the Microsystem 50 and simulation by the Moldex3D software. The results were relatively close to each other as shown in Figure 7.

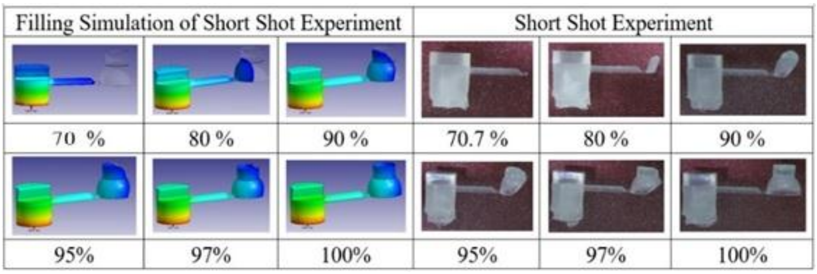
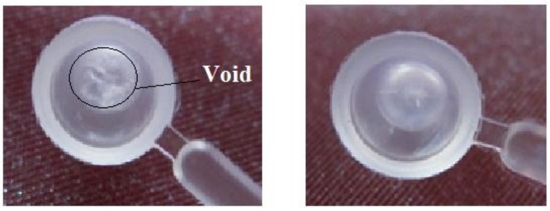


Figure 7 Comparison between filling simulation and experiments

The filling pattern between simulation and short shot experiments are similar (Figure 7). The volume of the cavity is only 27% of the total metered melt volume, so the melt starts to enter the cavity after 73% of the molten material has completely taken the space of the sprue, runner, and gate.

There was void in the thickest area of the molded part in the trial molding, as shown in Figure 8a; either an air trap or shrinkage would have caused this. The molding simulation, as seen in

Figure 9, shows that there was an air trap at the edges, but not in the center, of the part; a venting path was designed to prevent such a problem. When there is not enough material delivered into the cavity to compensate for material shrinkage during packing for a thick part, defects such as sink marks and voids will occur. When the melt close to the cavity surface solidifies more quickly, thicker frozen will prevent the melt from shrinking inwards, and instead will pull the inner material towards the surface of the part, thus resulting in the internal void shown in Figure 8a. When molding at higher melt and mold temperatures during the trial, it took longer for the melt to cool down, providing more chance to pack extra material into the cavity. The frozen layer grew more slowly, also helping to prevent void defects when molding at higher temperatures. The molded part without void shown in Figure 8b.



(a) (b)

Figure 8 A part result: **(**a) part with the void; (b) part without void

The elasticity and toughness properties of PP material provided the opportunity to successfully mold this micro part without draft angle design. Typical mold design suggests that a draft angle of 1/2^o is required for easy demolding; with a height of the upper part of the lens of 2.176 mm and a draft angle of 1/2^o, the difference between the diameter of the top and that of bottom of the upper part will be 0.019 mm. The mold was initially designed for making an LED lens using PC material. Since 0.019 mm is small and the luminous uniformity and viewing will decrease with the draft angle, no draft angle was designed in this study.

Trial moldings with PC and PMMA materials with the same mold system were conducted before using PP, but the parts could not be successfully removed from the mold since PC and PMMA are more rigid than PP. Draft angle should be designed in the molding of this LED lens in the future study using PC or PMMA material.

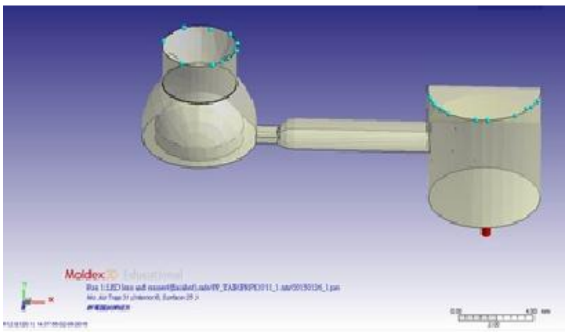


Figure 9 Moldex3D simulation of air trap location

4. CONCLUSION

This study has investigated the effect of micro-injection molding parameters on the size of shrinkage of double-concave spherical structures. Appropriate molding parameters should be set to successfully mold this micro part without defects. Melt temperature is the dominant factor in the molding of the part, because this affects the melt viscosity and the cooling rate, and subsequently influences the packing efficiency.

Successful molding using PP material was achieved in this study without consideration of a draft angle, which is not the same when molding more rigid PC and PMMA materials. A draft angle should be considered when molding micro parts with rigid and brittle materials, as it will be much easier for parts to be released cleanly from the mold.

5. ACKNOWLEDGEMENT

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