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Investigation of processing parameters in micro-thermoforming of micro-structured polystyrene film †

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Abstract

In this study, a thermoforming process for manufacturing micro-structured polystyrene (PS) films is investigated to characterize the effects of significant processing parameters. The present micro-thermoforming process utilizes a mold core with five concave rectangular grooves (each of width 0.4–1.2 mm and a depth of 1 mm). Two types of PS films (thicknesses of 50 and 190 μm) are employed to examine the effect of film thickness. Three main processing parameters namely heating temperature, heating time, and mold core temperature are analyzed. The results show that as the width of the groove in the mold core decreases, the forming ratio (depth-to-width ratio of the thermoformed micro-feature) slightly reduces, consequently indicating poor thermoforming. Both thin and thick PS films exhibit similar forming results under favorable conditions. However, when the processing conditions are not suitably applied, the thick film shows the worst result. From the design of experiment analysis using a normalized forming ratio, the mold core temperature is found to be the most influential factor in the thermoforming process of manufacturing micro-structured PS films.

Keywords: Forming quality; Micro-feature; Micro-thermoforming; Polystyrene film

1. Introduction

Thermoforming is one of the modern key polymer processing technologies. It is classified as a secondary shaping process of thermoplastic sheet and film [1]. In general, thermoforming mainly consists of heating the thermoplastic sheet or film and subsequently forming it in a cavity in a mold. In case of an amorphous plastic film, heating is performed slightly above the glass transition temperature of the film, thereby enabling relatively easy stretching and/or forming of softened film. Vacuum, air pressure, mechanical means, or their combinations are commonly employed to realize such a deformation of the film. After the forming step, the film is sufficiently cooled down for demolding the final product. Thermoforming has several advantages such as relatively low operating temperature, rapid production, low tooling cost, etc. In particular, the tooling cost for a thermoforming mold is much lower than that for injection molding [1-3].

Recently, a micro-thermoforming technique to fabricate precise micro-structured plastic films has been successfully demonstrated [4]. Because advanced micro-manufacturing technologies have been developed, micro- and nano-scale cavities can be accurately produced on the mold for thermoforming. Moreover, many plastic-based microfluidic systems have been investigated especially for various biomedical applications [5]. In this regard, micro-thermoforming is considered a promising mass production process of flexible and lightweight microfluidic systems because it is able to produce complicated micro-features on a relatively thin film [6]. As representative examples, a capillary electrophoresis chip [7], micro-container for cell study [8], cell culture chip [9], microfluidic lab-on-a-foil [10], and bioreactor [11] have been reported. In addition to the development of practical application products, great efforts have been put to improve the performance of the micro-thermoforming process and incorporate it with other manufacturing techniques [12-15]. This proves the great potential of micro-thermoforming as micro- and nano-manufacturing processes in various fields.

However, there are still some obstacles for the efficient utilization of micro-thermoforming in the mass-production of micro-structured films. In particular, non-uniform heating of film and irregular distribution of film thickness after thermoforming should be overcome [1]. Non-contact infrared radiative heating is commonly used for heating the film to be thermoformed. Because temperature of the heated film cannot be easily measured and a relatively large film is typically used,

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precise control of the film temperature is quite difficult. During thermoforming, the film is forcefully stretched, thereby reducing its thickness. Because the amount of stretching can vary from point to point owing to non-uniform temperature, the final product is likely to have irregular film thickness distribution. This can diminish the quality of the final micro-structured film or even produce defects such as punctures. In addition, the effects of processing parameters affecting the forming quality have not been deeply investigated so far.

In the present study, the micro-thermoforming experiment using polystyrene (PS) films was extensively carried out to investigate the effects of processing parameters. The developed micro-thermoforming setup and its performance were verified. The micro-thermoforming process was performed using a mold core with rectangular concave grooves of different widths. The various micro-features on the micro-structured PS film obtained from the micro-thermoforming process were characterized in terms of a forming ratio, film thickness variation, and a normalized forming ratio. In addition, a design of experiment (DOE) approach was used to analyze the detailed contribution of major processing parameters quantitatively.

2. Experimental

2.1 Thermoforming experiment

Fig. 1(a) shows the in-house micro-thermoforming setup used in the present study. It mainly consists of upper and lower parts, which are assembled to hold the mold core and plastic film together. The upper part has an infrared radiative heating element for film heating and a pressurizing unit, which can supply compressed air from an external air compressor. The lower part has a cavity with a perforated base plate where the mold core is placed. Air inside the cavity can be extracted through the perforated base plate using an external vacuum pump. In this manner, the heated plastic film can be formed using positive pressure (by compressed air from the upper part) and/or negative pressure (by evacuation from the lower part). The lower part also includes cartridge heaters to control the temperature of the mold core.

The mold core used in the present study is shown in Fig. 1(b). It consists of five concave rectangular grooves with different aspect ratios, i.e., ratio of depth to width. The width of the grooves ranges from 0.4 to 1.2 mm by a 0.2 mm increment, while the depth is a constant at 1 mm. For efficient venting of air entrapped between the plastic film and mold core, a sectioned mold core is designed and manufactured.

When the flat plastic film is placed on top of the mold core, which is heated to the setting temperature, infrared radiative heating of the film occurs. After the assigned heating time, the upper part is closed to create an enclosed cavity. The pressurized air supply and/or evacuation are then performed, thereby producing the micro-structured film, where the micro-features are formed as depicted in Fig. 1(c). In the present study, a PS film was selected as the thermoforming material. In particular, biaxially oriented PS films with thicknesses of 50 and 190 μm

Table 1. Processing parameters considered in the present study and their levels.

	Parameters	Level	
		1	2
A	Heating temperature (°C)	170	238
B	Heating time (s)	12	20
C	Mold temperature (°C)	55	110

Table 2. Experimental sets used in investigating the effects of processing parameters on forming quality.

Set #	Parameter level		
	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

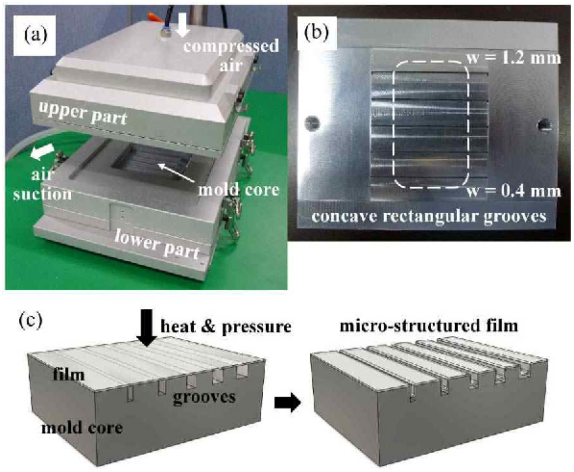

Fig. 1. (a) In-house micro-thermoforming setup used in the present study; (b) mold core with five concave rectangular grooves; (c) schematic illustration of the present micro-thermoforming experiment.

were used to investigate the effect of film thickness.

To examine the microfeatures manufactured by the micro-thermoforming process, cold mounting of the micro-structured film was carried out. A thermal curable elastomer (polydimethylsiloxane) was employed as the cold mounting material. It should be noted that a red ink was added during cold mounting to observe the transparent PS film clearly. Subsequently, the entire sample was carefully clamped and sliced to measure the cross-section of the micro-structured film using a microscope (Axio Lab A1, Carl Zeiss). In this manner, the cross-section of the micro-features in the film was measured without any damage.

2.2 Design of experiment (DOE) analysis of processing parameters

Various processing parameters determine the quality of micro-features in a micro-thermoforming process. The main parameters considered are either pressure or thermal factors. For example, pressure of compressed air and vacuum for evacuation determine the pressure difference between the upper and lower regions of the plastic film. This pressure difference, i.e., pressure factors, is the main driving force for inducing forming of the plastic film. Thermal factors include heating of the plastic film and mold core. Because a sufficiently high temperature of the plastic film is required to produce a permanent deformation, temperature of the radiative heating element and heating time should be carefully determined. While insufficient heating cannot produce effective forming of the plastic film, excessive heating will create defects such as tear and sag. In addition, the temperature of the mold core affects the cooling of the heated plastic film when the film is deformed and touches the mold core surface.

In the present study, while the pressure factors are kept constant (compressed air at 2 bar for around 40 s), thermal factors such as heating temperature, heating time, and mold core temperature are examined based on DOE analysis using a signal-to-noise (S/N) ratio [16, 17]. Table 1 shows the detailed conditions for each parameter, which are determined from a preliminary feasibility experiment. Because three parameters, each with two levels of conditions, are considered, an $L_4(2^3)$ orthogonal array is selected to determine the experimental sets (Table 2). It may be noted that the heating time tested in the present study is quite shorter than that used in the previously developed micro-thermoforming processes, which mainly utilized a conductive heating method.

3. Results and discussion

3.1 Verification

For verification of the developed micro-thermoforming setup and its application to the thermoforming process, a preliminary experiment was carried out. Among the various cases, Fig. 2 shows the representative ones. To characterize the micro-features formed in the PS film, a forming ratio defined as the depth-to-width ratio of the micro-feature is employed. The detailed dimensions such as depth and width of the micro-features were measured from the cross-sectional microscopic view of the sliced film. Because a larger depth and/or smaller width of the concave rectangular groove tend to prevent facile formation of the film during the micro-thermoforming process, the forming ratio of each groove can show the relative degree of forming.

In the case of the thin PS film (50 μm thick), heating temperature, heating time, and mold core temperature were set to be 238 °C, 20 s, and 55 °C, respectively. Similarly, 170 °C, 30 s, and 55 °C were used for the parameters of the thick PS film (190 μm thick). It should be noted that the selected heating temperatures correspond to the maximum and minimum condition to obtain reliable micro-thermoforming. For example, when a heating temperature higher than 238 °C was applied to the thin PS film, severe damage to the heated PS film occurred,

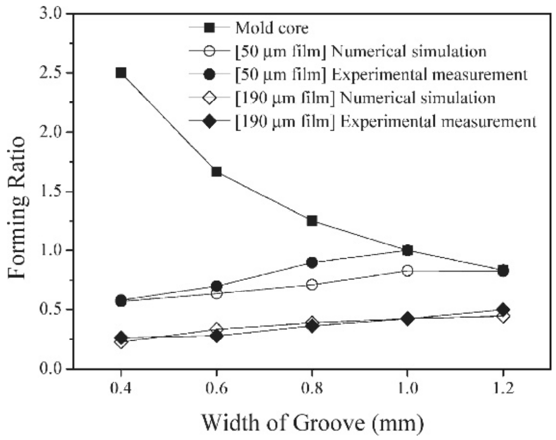

Fig. 2. Comparison of numerical and experimental results of forming ratios.

thereby prohibiting stable thermoforming. The thick PS film could not be deformed if the heating temperature was lower than 170 °C. In this regard, these two cases are selected for representative purposes showing the extreme situations in terms of heating temperature.

In addition, the forming ratio for each case was calculated from the numerical simulation as indicated in Fig. 2. The commercial finite element analysis software (ANSYS Polyflow) was used to obtain the numerical results. The same processing conditions as the micro-thermoforming experiment were applied. Depth and width of each micro-feature in the thermoformed film were measured from the numerical solution, which were used to calculate the forming ratios.

As shown in Fig. 2, the forming ratios of the PS films were found to increase gradually with increasing width of the rectangular groove in the mold core. This is attributed to the preferable geometry of the groove, i.e., when the depth is the same, the groove with a larger width has a wider opening, thereby providing better deformation of the plastic film. Similarly, the forming ratio of the groove in the mold core can be interpreted as a measure of difficulty in the deformation or forming of the plastic film. In addition, there was no significant discrepancy between the experimental and numerical results. It should be noted that because the detailed procedure of the numerical simulation is out of the scope of the present study, it will be discussed later.

3.2 Forming ratio of micro-features

Four experimental sets described in Table 2 were determined based on DOE analysis for efficient investigation. Among the investigated cases, the experimental sets #1 and #3 were found to be the worst and best cases, respectively. Fig. 3 shows the microscopic views of the representative micro-features in the thermoformed PS film. These micro-features were obtained on the rectangular groove with the smallest width (0.4 mm). The groove with the smallest width among the others inherently prohibits easy thermoforming of the plastic film. However, this characteristic showed distinct changes in the micro-feature when the processing conditions of the micro-thermoforming process were changed.

When an unsuitable processing condition, such as the experimental set #1 in this study, was used, there was no obvious forming of the plastic film on the groove (Figs. 3(a) and (c)). Furthermore, although slight forming of the micro-feature was observed in the thin film as shown in Fig. 3(a), no clear evidence of forming of the micro-feature was observed in the case of the thick plastic film (Fig. 3(c)). To be sufficiently heated for successful thermoforming, the thicker film requires more heating than the thinner film. Hence, the applied thermal processing conditions might not increase the temperature of the thick film up to a sufficient level for thermoforming. In contrast, a favorable processing condition (e.g., set #3) was able to produce good forming of the plastic film. As shown in Figs. 3(b) and (d), similar deformation of the plastic film could be obtained for both thin and thick films. This indicates that the applied conditions could provide proper heating of both the films, thereby resulting in a similar temperature level for each case.

It should be noted that thinning of the plastic film occurred during thermoforming. For example, the difference of the film thicknesses after the micro-thermoforming process could be clearly observed in Figs. 3(c) and (d), although the same plastic films of 190-μm thickness were used. The different processing conditions used in each case resulted in both distinctly formed micro-features and change in thickness. Because excessive stretching of the plastic film occurs during a typical thermoforming process, the thickness of the formed film reduces together with shape deformation.

Fig. 4 shows the forming ratios for two representative experimental sets in detail. As the width of the groove in the mold core decreases, the forming ratio slightly reduces, indicating poor thermoforming. Both the thin and thick films exhibit similar forming result under a favorable condition (e.g., set #3). In particular, for the grooves with a large width, such as 1.0 and 1.2 mm, almost completely formed micro-features could be obtained in terms of the forming ratio. However, when the processing conditions are not suitably applied (set #1), the thick film shows the worst result. This can be attributed to the insufficient heating of the thick PS film.

3.3 Film thickness distribution

During micro-thermoforming, the heated plastic film is clamped along its outer boundary. Therefore, the film stretches when pressure difference is applied across it. This stretching is the main mechanism of forming of the heated plastic film. However, as the film is elongated in the lateral direction, its thickness automatically reduces. The reduced thickness causes certain disadvantages such as non-uniform thickness over the entire film and puncture or tear. In addition, thickness reduction reflects the degree of stretching of the film, which is closely related to the forming quality. In this regard, the thickness of the micro-thermoformed film was measured from the top, side, and bottom positions of the micro-feature.

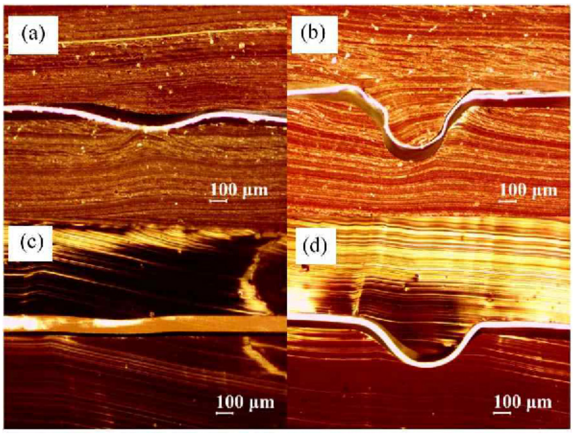

Fig. 3. Cross-sectional microscopic views of the micro-structured films in a 0.4 mm wide groove: (a) Set #1 with 50 μm thick film; (b) set #3 with 50 μm thick film; (c) set #1 with 190 μm thick film; (d) set #3 with 190 μm thick film.

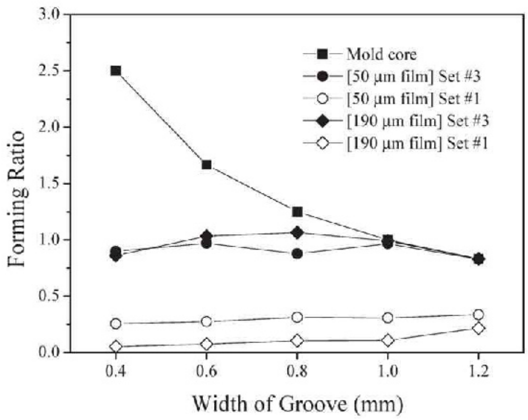

Fig. 4. Forming ratios for each representative case.

Figs. 5(a) and (b) show the film thicknesses at three measuring positions for the 50 and 190 μm thick films, respectively. It may be noted that the thickness values measured for the five grooves were used together to obtain the average film thickness. For all the cases, the thickness was found to reduce from the top to bottom positions. This is because the bottom area of the micro-feature typically experiences the largest deformation or stretching by the applied pressure difference. In addition, sets #1 and #3 show the largest and smallest film thickness values, respectively. Similar to the forming ratio discussed earlier, better forming of micro-features requires larger deformation or stretching, consequently resulting in reduced film thickness. Film thickness may be used as a forming measure because it is related to the stretching behavior of the film during the micro-thermoforming process.

3.4 Forming quality and contribution of parameters

Although the previously introduced forming ratio directly

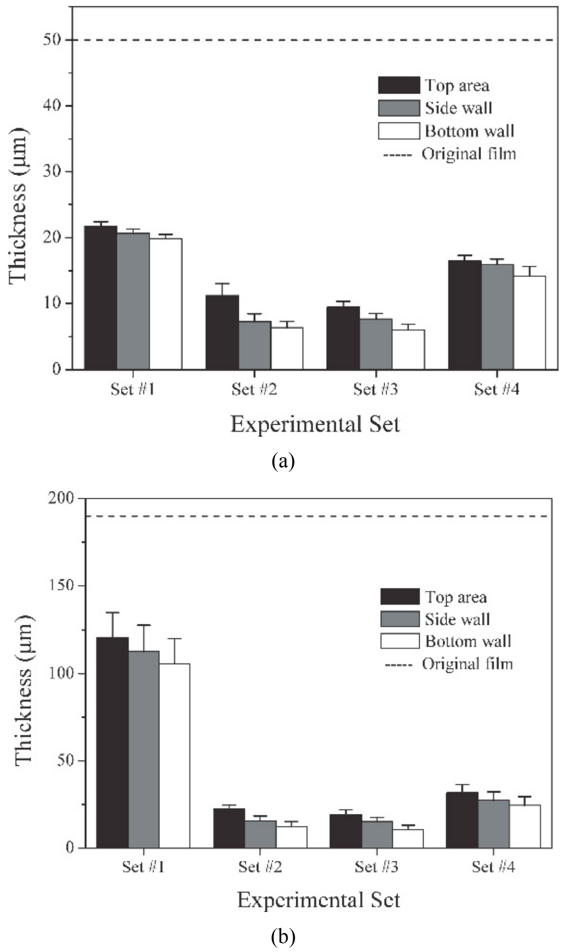

Fig. 5. Film thickness distribution at the top, side, and bottom areas: (a) 50; (b) 190 μm thick films.

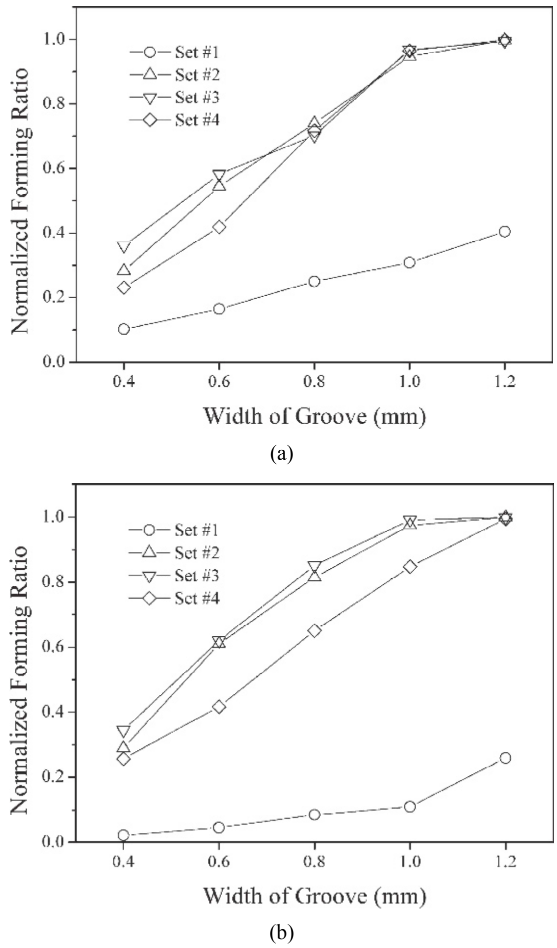

Fig. 6. Normalized forming ratios: (a) 50; (b) 190 μm thick films.

indicates the amount of deformation of the plastic film in the concave rectangular groove in the mold core, it does not show the forming quality – the amount of forming with respect to the groove. In this regard, a new variable with a normalized forming ratio was employed to evaluate the forming or replication quality directly. The normalized forming ratio in the present study was calculated by dividing the forming ratio of the film by that of the groove in the mold core. It should be noted that because the width of the micro-feature in the formed film is the same as that of the groove in the present study, the normalized forming ratio represents the forming depth.

The calculated normalized forming ratios are shown in Fig. 6. For both the cases of 50 (Fig. 6(a)) and 190 μm (Fig. 6(b)) thick films, the normalized forming ratios increased as the width of the concave rectangular groove increased. In particular, a normalized forming ratio of around 1 indicates that complete thermoforming could be obtained for most of the experimental sets when the width of the groove was 1.2 mm. This can be attributed to the forming ratio, i.e., aspect ratio, of the groove in the mold core. When the groove's forming ratio is reduced, more deformation or stretching of the film into the deep groove is required to achieve complete thermoforming. Unless more pressure difference is applied, only a little forming depth of the plastic film can be obtained for the smaller width cases.

When favorable processing conditions, such as set #2 or #3, were applied, there was no significant discrepancy between the thin and thick plastic film cases. Although thick films are usually more difficult to be formed or deformed during microthermoforming, it can be overcome by applying suitable processing conditions. However, when unsuitable conditions were applied, such as set #1 in the present study, the thick plastic film was found to show the worst forming quality, as shown in Fig. 6(b). This represents that the effect of film thickness becomes distinct when the processing conditions are not correctly determined.

To elucidate the effect of the thermal factors considered in this study on the forming quality, DOE analysis using S/N ratio was carried out. In the DOE analysis, the 'larger-the-better' type S/N ratio was calculated based on the normalized forming ratio, which can represent the forming quality efficiently. The contribution of each parameter for the thin and thick PS films, which was obtained from the DOE analysis, is shown in Fig. 7. It was found that the mold core temperature

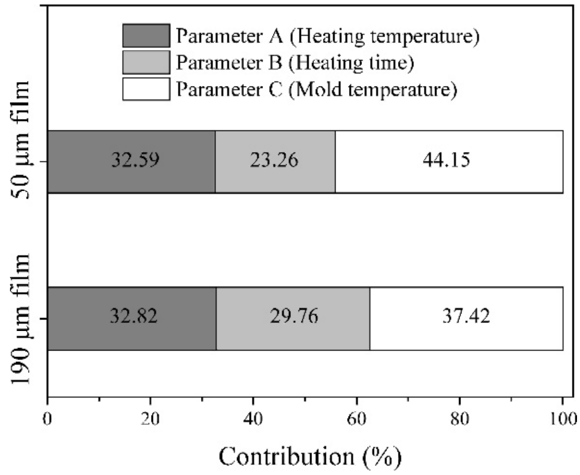

Fig. 7. Contribution of each parameter to the forming quality.

was the most influential factor regardless of the film thickness. In addition, the heating temperature was found to be quite important for good forming quality. This implies that it is important to minimize the temperature difference between the heated plastic film and the mold core surface during the micro-thermoforming process. The relatively large difference in temperature directly results in rapid cooling of the plastic film, thus prohibiting the facile deformation or stretching of the film into the mold core groove. Moreover, the contribution of the heating time became large when the film thickness was increased. Because thick plastic films require more heat to deform sufficiently than the thin film, the heating time may also have a meaningful effect together with the heating temperature.

4. Concluding remarks

In the present study, a micro-thermoforming process to fabricate micro-structured PS films was developed. In particular, the effect of major processing parameters on the forming quality of micro-features was investigated. We concluded that as the width of the groove in the mold core decreased, the forming ratio slightly reduced consequently indicating poor thermoforming. In addition, a similar trend was observed when a normalized forming ratio was employed to represent the forming quality. The formed films showed the smallest thickness at the bottom position regardless of the initial film thickness and processing conditions, which indicates that the bottom area experiences the largest stretching during thermoforming. From the DOE analysis using the normalized forming ratio, the mold core temperature was found to be the most influential factor for better forming quality. The present investigation can be beneficial to establish a precise micro-thermoforming process and broaden its practical applications.

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