Study on thickness distribution of thermoformed medical PVC blister

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Abstract. Vacuum forming has many advantages over other plastic forming processes due to its cost effectiveness, time efficiency, higher product precision, and more design flexibility. Nevertheless, when pressures greater than the atmospheric value are required to force the thermo-plastic into more intimate contact with the mold surface, pressure forming is a better choice. This paper studies the process of air-pressure thermoforming of plastic sheet, and focuses on medical blister PVC products. ANSYS POLYFLOW tool is used to simulate the process and analyze the wall thickness distribution of the blister. The influence of mold parameters on the wall thickness distribution of thermoformed part is thus obtained through simulation. Increasing radius between mold and side wall at the bottom of blister and draft prove to improve the wall thickness distribution.

1 Introduction
Vacuum forming is a simplified version of thermoforming, whereby a sheet of plastic is heated to a forming temperature, stretched onto a single-surface mold, and forced against the mold by a vacuum, with usual pressure ranging from 0.01 to 0.03MPa. It is the pressure that primarily dictates the quality features of thermoformed products. For thick sheet or part with complex shape, the usual forming pressure may be insufficient, leading to poor details in formed part such as vague images, surface texts and etc., or even failure in manufacturing [1-3]. Pressure thermoforming is so called as is accomplished by sealing the heated plastic sheet on the edge of the mold base, removing the air from within the mold cavity, and thus forcing the material up against the mold surface through atmospheric pressure [4]. Figure 1 shows the process of pressure thermoforming.

(a) preheat  (b) clamp  (c) pressure thermoforming

Figure 1: Process of pressure thermoforming

However, due to lack of detailed information regarding to the molding process and theoretical support, uncertainties in thermoforming product design, mold structure and parameters can only be reduced through experiments, which is costly and time consuming [5]. CAE technology is applicable to the problem through simulating the thermoforming process [6-8], which results in a better understanding of the flow of melt in the process and an improved prediction of the wall thickness distribution of part.
This technology greatly shortens the development period of industrial parts and provides reference to the design and manufacturing of mold \[9\].

2 CAE analysis of pressure forming

2.1 Create analysis task model and solution

According to the air-pressure thermoformed model in real manufacturing process shown in Figure 2, the geometric model is established in SolidWorks. To improve the calculation efficiency, simulation of one blister is made. Since the thickness of PVC sheet is much less than its length and width, a thin shell unit is used to build up a 3D thermal analysis model \[10\]. Figure 3 shows the geometric model used in CAE. The upper Figure stands for the original PVC sheet, while the lower Figure is the model of air-pressure thermoformed part. The size of original PVC sheet is: 30 mm in length and width, and 0.30 mm in thickness. The PVC sheet and air-pressure thermoforming model are separated by 30mm, and the depth of mold is 16mm.

![Figure 2: Thermoforming mold](image1)

![Figure 3: Geometric model](image2)

In ANSYS POLYDATA, the nature of the task model is created. In accordance with real production of air-pressure thermoforming, the settings of parameters are as follows: the speed of blister is 35 r/min, the velocity constant of model is 300 mm/s, the pressure constant is 0.6MP, and the blow air time is 0.17s. The layer of PVC has the following material properties: a constant viscosity of 105pa·s, and a density of 1.4×10⁻³g/mm⁻³. Inertia force effects are considered.

2.2 The results of Molding

The thickness distributions of thermoforming trays at different time periods are shown in Figure 4. The original thickness of PVC sheet is 0.30mm. To demonstrate thickness variation of the sheet in cloud chart, the same scale range is set manually, ranging from 0.05mm to 0.30mm.

![Figure 4: Thickness distributions](image3)
Figure 4: Distribution of blister thickness

As shown by the contours of thickness distribution, PVC sheet does not contact the die at the time of 0.0001s. When it comes to 0.102s and the die moves upward, the PVC sheet near the holding portion sticks onto the die and produces a sealed cavity. The sheet does not deform at this time. At the time of 0.110s, the blowing valve opens, and cylinder shape is produced by compressing air. Heated PVC material uniformly flows under the air pressure. The overall blister thickness of PVC sheet is reduced evenly, as shown at the time of 0.122s. When the PVC sheet begins to stretch onto the die, it blows up. With the ongoing of deforming, the mold generates different irregular deformation. At the time of 0.126s and 0.130s, the sheet thickness decreases irregularly. At the bottom of the side near the tray, blister and the corner of the material contact the die. At the time of 0.3s, the biggest deformation and least thickness occur. The thermoforming process is over.

Figure 5 is the cloud chart of thickness distribution at final time of 0.30s. The thickness of the tray products gradually reduces from the top to the bottom. The top red tray around the edge is with the maximum thickness, which is close to the original thickness of PVC sheet, while the bottom blue tray is with the minimum thickness, being only 0.53mm, less than 1/5 of the original. The overall thickness distribution is not uniform.

Figure 5: Distribution of blister thickness at time is 0.3s

By analyzing the simulated process, we find that: (1) Within the process of air-pressure thermoforming, the melt and the die, or the melt and the plunger, contact at a certain stage, which restricts the flow of PVC melt and influences the thickness distribution of hot forming blister products; (2) Air-pressure thermoforming is not suitable for parts with a deep cavity. Greater depth will cause over thinning at the bottom of the formed part; (3) On the whole, the thickness of air-pressure thermoforming products decreases gradually.

3 Thermoforming experiment validation

Air-pressure thermoformed blisters manufactured in industry are shown in Figure 6. Ten trays are randomly selected for the experiments, and the thickness value of each blister is measured at different measurement points. The average value of each point is shown in Table 1. The chart of the thickness and corresponding positions of each measurement point is thus demonstrated in Figure 7.
Figure 6: Blister products of thermoforming

Figure 7 shows that the part with the maximum thickness of the pressure thermoformed pallet is on the edge (A), and that with the minimum thickness is between the bottom blister and transition (D), with the thickness value being 0.051 mm. The comparison of experiments with the numerical simulation results are shown in Figure 8, whereby the thinning of the sheet and the position of the thin section are consistent. Figure 8 shows that the thickness distribution of thermoformed parts through simulation and in real industrial manufacturing is similar. Simulation results are more reliable in that it predicts the final thickness distribution of molding tray more accurately.

Table 1: Experimental data

| point | A   | B   | C   | D   | E   |
|-------|-----|-----|-----|-----|-----|
| 1     | 0.283 | 0.175 | 0.074 | 0.038 | 0.112 |
| 2     | 0.292 | 0.183 | 0.085 | 0.045 | 0.111 |
| 3     | 0.294 | 0.192 | 0.122 | 0.042 | 0.108 |
| 4     | 0.312 | 0.201 | 0.099 | 0.032 | 0.110 |
| 5     | 0.30  | 0.184 | 0.095 | 0.048 | 0.110 |
| 6     | 0.275 | 0.186 | 0.097 | 0.037 | 0.116 |
| 7     | 0.30  | 0.172 | 0.089 | 0.046 | 0.105 |
| 8     | 0.282 | 0.185 | 0.082 | 0.044 | 0.124 |
| 9     | 0.291 | 0.198 | 0.087 | 0.041 | 0.102 |
| 10    | 0.311 | 0.164 | 0.120 | 0.037 | 0.112 |
| average | 0.294 | 0.184 | 0.095 | 0.041 | 0.111 |

Figure 7: Thickness distribution

Figure 8: Comparison chart of thickness distribution
4 The influence of the mold parameters

4.1 The influence of the radius
In order to avoid stress concentration caused by internal stress or shock in the process of drafting, border radius is often used in plastic parts. In mold design, round transitions are used as many as possible at the inner corner of mold, at the corner of the blister and in the place of blister thickness transition [11-13]. Round transition not only helps avoid stress concentration, improves strength and appearance of products, but also frees the flow of heated plastics [14].

The weakest spot of the thermoformed blister is at the cross corner between the bottom and sidewall, as both shown in the experimental measurement and simulation. Under the same conditions, blister thickness distribution of the tray is simulated at radius values R = 0, 0.5, 1, ..., 5. Table 2 is the maximum and minimum values of blister thickness obtained by simulations with different radius. Table 2 indicates that with the increase of mold radius, maximum thickness value remains constant while the minimum blister thickness value changes obviously. The minimum value increases with the increase of radius. To save space, only the cases with corner radius of 0, 3, 5mm are listed. Distribution of blister thickness with different fillet radius is shown in Figure 9.

| Radius /mm | Max. thickness /mm | Min. thickness /mm |
|------------|--------------------|--------------------|
| 0          | 0.318              | 0.043              |
| 0.5        | 0.317              | 0.045              |
| 1.0        | 0.316              | 0.047              |
| 1.5        | 0.317              | 0.051              |
| 2.0        | 0.318              | 0.054              |
| 2.5        | 0.317              | 0.056              |
| 3.0        | 0.315              | 0.059              |
| 3.5        | 0.315              | 0.061              |
| 4.0        | 0.316              | 0.063              |
| 4.5        | 0.316              | 0.065              |
| 5.0        | 0.316              | 0.068              |

Figure 9: Blister thickness distribution at different radius
From Figure 9, it is found that: (1) When the round radius is 0, the thinnest part occurs in the sidewall and the bottom of the round corner of the blister. The minimum thickness is only 0.043mm and the maximum is 0.318mm. The thickness distribution blister is uneven. (2) When the round radius increases to 3mm, the minimum thickness value increases to 0.059mm and the maximum decreases to 0.315mm. The distribution of blister thickness is more uniform than that with radius of 1mm. (3) When the round radius continues to increase to 5mm, the minimum thickness value increases to 0.068mm, and the thickness distribution and the performance of tray are significantly improved. However, there are also some limitations as to what we can do with the radius in real production, and therefore an appropriate radius should be selected.

4.2 Effect of stripping slope

In the thermoforming process, more draft of the mold helps to improve the distribution of the wall thickness. The contours of distribution of tray blister thickness are shown in Figure 10 when the round radius of bottom of the mold is 0mm, and stripping gradient is 0°, 3° and 5° respectively. The contours of distribution of tray blister thickness are shown in Figure 11, when the round radius is 5mm and stripping gradient is 0°, 3° and 5°, respectively.

![Figure 10: Distribution of blister thickness at different draft angles with R=1mm.](image)

As shown above, the thickness distribution changes with different stripping slopes. The minimum thickness of the molded part is 0.044mm, 0.047mm and 0.048mm in Figure 10 and the minimum thickness of the molded part is 0.066mm, 0.068mm and 0.070mm in Figure 11. When R=1mm and R=5mm, the minimum values of blister thickness increases with stripping slopes. The general value of stripping slope is α=2°~6° [15]. When the value of thermoformed products is high, the lower limit is taken. When it is low, the upper limit is taken. Therefore, under permitted conditions, increasing stripping slope can appropriately improve the distribution of blister thickness.
Figure 11: Distribution of blister thickness at different draft angles with $R=5\text{mm}$.

5 Conclusion
The experiments show that the thickness of air-pressure thermoformed part decreases from top to bottom. CAE simulation is verified to help obtain appropriate thickness distribution in thermoforming. Furthermore, the radius between the mold bottom and the side wall of blister influences the distribution of thickness.

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