Research of Cooling Shrinkage Deformation for Multi-point Thermoforming of Resin Sheet

Heli Peng 1*, Xing Han1 and Cheng Jin1

1Shanghai Spaceflight Precision Machinery Institute, Shanghai, 201600, China
*Corresponding author’s e-mail: ph112616040811@126.com

Abstract. The multi-point thermoforming (MPTF) process of resin sheet are introduced, the material parameters of resin sheet and elastic cushion are got, the finite element model of MPTF for resin sheet is set up, and numerical simulations of cooling shrinkage deformation of resin sheet are carried out. The influence factors such as material, thickness and radius are studied by lots of numerical simulation, and the shape compensation of cooling shrinkage deformation is put forward to deduce the forming error. Then, MPTF experiment of spherical part with Polymethylmethacrylate (PMMA) sheet is put forward, and the comparisons of shape error between experimental parts and object surfaces are obtained. Consequently, it is confirmed that PMMA sheet formed by MPTF after shape compensation has good shape accuracy.

1. Introduction

Resin sheet is used in many fields for its good comprehensive performance, such as low density, high specific strength, corrosion preventive, good ductility and good insulation. There are three kinds of methods to form resin sheet, which are compression molding, thermal diaphragm forming and bulging forming. While all the above methods need specific mould, which is hard to achieve personal manufacture, so it is urgent to demand flexible adjustable die to form resin sheet.

In the past two decades, lots of research were carried out to form resin sheet by flexible discrete die technology. Kleespies[1] combined simple variable geometry mold and vacuum thermoforming to form compound curved surfaces, discussed the effects of variable geometry mold to forming quality, and proposed flexible forming of compound curved surfaces has broad application prospects. Walczyk[2]designed and developed flexible experimental machine by combining the reconfigurable tooling and vacuum thermoforming to form composite aircraft parts, the efficiency of heating surface and forming defects are analyzed, and the method of improving the forming quality by placing elastic pad between reconfigurable tooling and composite sheet is pointed out. Simon[3] developed a simple reconfigurable tooling system to form plastic shields, where specific punch elements are used to improve the continuity of reconfigurable tooling system is composed of 578 elements, and the effects of forming pressures to surface quality and forming quality are analyzed by numerical simulation and experiment. Su[4] proposed the multi-point thermoforming to manufacture freeform panels by combining the multi-point forming and thermoforming. Peng[5,6] developed multi-point thermoforming(MPTF) machine and studied the feasibility and practicability through lots of numerical simulations and experiments for multi-point forming of PC sheet.

Although the resin sheet can be formed by MPTF technology, the shrinkage of resin sheet in the cooling stages is unavoidable, and which affect the outline shape. So, it is necessary to study the cooling shrinkage deformation and its influencing factors in order to obtain good forming precision.
2. MPTF Process and Finite Element Model

2.1. MPTF Process
The MPTF process of resin sheet can be divided to four steps, as shown in Figure 1. The multi-point die was adjusted based the objective surface in the step one, the resin sheet was heated by heating rods until the temperature accord with forming temperature, then the compressed gas is poured into forming box through air pimp until the resin sheet accords fully with the multi-point die, finally the resin product is removed when it backs to room temperature.

Figure 1. The MPTF Process of Resin Sheet

2.2. Material Parameters
Polycarbonate(PC) and Polymethylmethacrylate(PMMA) are selected as the objective materials. the glass transition temperatures of PC and PMMA are measured as 145℃ and 105℃ by dynamic mechanical analysis respectively. Generalized Maxwell model is selected to describe the viscoelastic behavior of PC and PMMA, and the Prony series is used to describe relaxation property in ABAQUS, as shown in the equation (1):

\[ e(t) = 1 - \sum_{i=1}^{n} e_i (1 - \exp(-\frac{t}{\tau_i})) \]

(1)

Where \( e_i \) and \( \tau_i \) are coefficients of Prony equation.

The Prony coefficients of PC and PMMA are listed in Table 1. Based on the equivalent conversion principle of time and temperature, the parameters of Williams-Landel-Ferry (WLF) are calculated [7]. The constants of C1 and C2 for PC are 22.64 and 102.51, and that for PMMA are 6.71 and 65.01, respectively. The thermostable silica is selected as the material of elastic cushion, and Mooney-Rivlin model is used to describe its mechanical behavior [8], the material parameters of thermostable silica is shown in Table 2.

| Materials | Parameters | Numbers | i=1 | i=2 | i=3 | i=4 | i=5 |
|-----------|------------|---------|-----|-----|-----|-----|-----|
| PC        | \( e_i \)  | 0.3473  | 0.2628 | 0.3667 | 0.0139 | 0.0072 |
|           | \( \tau_i \) | 0.0715  | 0.5027 | 3.4399 | 33.276 | 411.04 |
| PMMA      | \( e_i \)  | 0.2788  | 0.1589 | 0.2729 | 0.2506 | 0.0403 |
|           | \( \tau_i \) | 0.0136  | 0.1049 | 1.3188 | 11.379 | 569.62 |

| Parameters | Temperature(℃) | 110 | 120 | 130 | 150 | 160 | 170 |
|------------|----------------|-----|-----|-----|-----|-----|-----|
| \( c_{ii} \) |                | 0.2011 | 0.2081 | 0.179 | 0.1434 | 0.1035 | 0.0655 |
2.3. Finite Element Model of MPTF
Spherical part is selected as the objective part, and numerical simulation of MPTF for resin sheet are put forward by ABAQUS. Due to the symmetry, only a quarter of finite element model is analyzed, as shown in the Figure 2, which is composed of resin sheet, silica cushion and multi-point die. The resin sheet is modeled with quadrilateral shell element S4R. The size of elastic cushion is 400×400×20mm, which is modeled with hexahedral solid element C3D8R. The size of multi-point die is 400×400mm, which only retains the hemispheric end, and is simplified to rigid shell surface and modeled with bilinear quadrilateral three dimensional rigid element R3D4. On the two symmetrical planes, the displacements normal to the planes and the rotations around the planes are constrained. Effective hourglass control techniques are used to avoid the spurious deformation modes when finite element simulations.

| C_{i1} | 0.1911 | 0.172  | 0.1998 | 0.2356 | 0.2763 | 0.3102 |

3. Numerical simulation of cooling shrinkage deformation

3.1. Cooling shrinkage deformation of MPTF
Dynamic explicit algorithm and static implicit algorithm are combined to simulate the cooling shrinkage deformation of resin sheet, which contain four steps. The first step: the MPTF process is simulated by dynamic explicit algorithm and viscoelastic model. The second step: the cooling process from forming temperature to glass transition temperature is simulated by dynamic explicit algorithm. The third step: the simulated results of the second step are imported to static implicit module. The fourth step: the cooling process from glass transition temperature to room temperature is simulated by static implicit algorithm and elastic model. The central point of formed part is constrained when numerical simulation of cooling shrinkage deformation, the displacement change of spherical part with different temperatures is shown in Figure 3. It can be found that the lower the temperature is, the larger the shrinkage deformation will be.

Figure 2. The FEM of MPTF for Resin Sheet
3.2. Influence Factors of Cooling Shrinkage Deformation

When the spherical radius is 500mm, the thickness of resin sheet is 4mm, two kinds of materials are investigated, the forming temperature of PC sheet is 150℃ and that of PMMA sheet is 110℃. The cooling shrinkage deformation of spherical part with PC and PMMA along the line OC is shown in Figure 4(a). When the material is PC, the maximum value of cooling shrinkage deformation is 5.4mm. While the material is PMMA, the maximum value of cooling shrinkage deformation is 2.5mm. The reason is that PMMA has a smaller thermal expansion coefficient and a lower glass transition temperature, which lead to a smaller shrinkage deformation.

When the spherical radius is 500mm, the material is PC sheet, the forming temperature is 150℃, four kinds of thicknesses of PC sheet are investigated. The cooling shrinkage deformation of spherical part with different thicknesses along the line OC is shown in Figure 4(b). When the thickness is 2mm, the maximum value of cooling shrinkage deformation is 9.3mm. With the thickness increase to 3mm, the maximum value of cooling shrinkage deformation decreases to 7.4mm. When the thickness increases to 5mm, the maximum value of cooling shrinkage deformation is 3.6mm. The result shows that the thicker the thickness is, the smaller the cooling shrinkage deformation will be. The reason is that a thicker PC sheet has stronger capability to resist shrinkage deformation.

When the material is PC sheet, the thickness of PC sheet is 4mm, the forming temperature is 150℃. The cooling shrinkage deformation of line OC on spherical part with four kinds of radii is shown in Figure 4(c). It can be found that the smaller the spherical radius is, the smaller the cooling shrinkage deformation will be, but the difference of cooling shrinkage deformation for different radius is small. The reason is that a larger radius has smaller capability to resist shrinkage deformation.

4. Figures Compensation of Cooling Shrinkage Deformation

The cooling shrinkage deformation of resin sheet is influenced by many factors such as the material, thickness and radius. It is difficult to decrease cooling shrinkage deformation by rigid die, while the
multi-point is flexible, which can be changed the shape quickly. So the method of shape compensation is used to reduce the deviation generated by cooling shrinkage in this paper.

Figure 5 shows the schematic diagram of target surface modification, where \( Z_{obj}(x, y) \) is the objective shape and \( Z_i^p(x, y) \) is the formed part after the \( i \)th modification, the error can be express by the following equation

\[
Z_i^err(x, y) = Z_{obj}(x, y) - Z_i^p(x, y)
\]  

(2)

Considering the shrinkage deformation of resin sheet, the new objective shape is structured by increase the shape error \( Z_i^err(x, y) \) multiply the coefficient \( C_i(x, y) \) on the basis of formed part after the \( i \)th modification, as shown in the equation.

\[
Z_i^{obj}(x, y) = Z_{i}^{obj}(x, y) + C_i(x, y)Z_i^{err}(x, y)
\]  

(3)

MPTF of spherical part with PC sheet is selected to verify the validity of shape compensation. When the size of multi-point die is 400×400mm, the spherical radius is 500mm, the thickness of PC sheet is 2mm and the forming temperature is 150℃. The outline shape of line OC on spherical part with shape compensation is shown in Figure 6. It can be found that the more the compensation times is, the smaller the deviation between actual shape and objective shape will be, and the final shape of spherical part near the objective shape after twice compensation.

5. MPTF Experiment of Spherical Part
The PMMA sheet with size of 400×400×2mm is selected as the experimental material, and which is formed at the temperature of 150℃. Thermostable silica is chosen as the elastic cushion, whose size is 400×400×20mm. Figure 7 shows the experimental photo of spherical part after twice compensation. It can be found that the spherical part has good profile shape. Three-Dimensional Sensing System (3DSS) was used to measure the forming precision. Figure 8 shows the shape error of spherical part by contrasting the node data information between experimental part and the objective surface. It shows that about 90% of the shape error ranges from -0.4mm to 0mm, which presents that the experimental parts coincides with the object surfaces.
6. Conclusions
The MPTF process of resin sheet is introduced, and the material parameters of resin sheet and elastic cushion are obtained. The process of cooling shrinkage deformation for MPTF of resin sheet is simulated, the results show that can be found that the shrinkage deformation of spherical part increase with the decrease of temperature. The influence factors of cooling shrinkage deformation are studied. The results show that the smaller the thermal expansion coefficient is or the thicker the thickness is or t larger the radius is, the smaller the cooling shrinkage deformation will be. Then shape compensation of multi-point die is used to reduce the deviation, which shows that the more the compensation times is, the smaller the deviation between actual shape and objective shape will be. Finally, the MPTF experiment of PC sheet is done, the result shows that the spherical part has good profile shape and forming quality by 3DSS, which illustrate that the method of shape compensation is practical to impose the forming precision.

Acknowledgements
This project was supported by National Science Foundation of China (51505278).

References
[1] Kleespies, III.H.S., Crawford,R.H. (1998) Vacuum Forming of Compound Curved Surfaces with A Variable Geometry Mold. Journal of manufacturing systems, 17(5): 325-337.
[2] Walczyk, D.F., Hosford, J.F., Papazian, J.M. (2003) Using Reconfigurable Tooling and Surface Heating for Incremental Forming of Composite Aircraft Parts. Journal of manufacturing science and engineering, 125(2): 333-343.
[3] Simon, D., Zitzlsberger, S., Wagner, J., et al. (2013) Forming Plastic Shields on A Reconfigurable Tooling System. 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production.
[4] Simon, D., Kern, L., Wagner, J., et al. (2014) A Reconfigurable Tooling System for Producing Plastic Shields. Procedia CIRP, 17: 853-858.
[5] Su, S.Z., Li, M.Z., Liu, C.G., et al.(2012) Flexible Tooling System Using Reconfigurable Multi-Point Thermoforming Technology for Manufacturing Freeform Panels. Key Engineering Materials, 504: 839-844.
[6] Peng, H.L., Li, M.Z., Liu, C.G., et al. (2013) Study of Multi-Point Forming for Polycarbonate Sheet. The International Journal of Advanced Manufacturing Technology, 67: 2811-2817.
[7] Peng, H.L., Li, M.Z., Liu, C.G., et al. (2014) Numerical simulation of multi-point forming accuracy for polycarbonate sheet. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 228(2): 87-96.
[8] Williams, M.L., Landel, R.F., Ferry, J.D.(1955) The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-Forming Liquids. Journal of the American Chemical Society, 77(14): 3701-3707.
[9] Al-Qureshi, H.A. (2002) Analysis of Simultaneous Sheet Metal Forming Operations Using Elastomer Technique. Journal of Materials Processing Technology, 125-126: 751-755.