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# Numerical simulation and experiment of wrinkle for multi-point thermoforming of resin sheet

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**Abstract.** The multi-point thermoforming (MPTF) process of resin sheet is introduced, the glass transition temperature of polycarbonate (PC) sheet is tested, and the material parameters of PC sheet are got. Numerical simulation of wrinkle for spherical part is carried out by ABAQUS, and the generated result of wrinkle with MPTF is elaborated. The effects of thickness, forming temperature and spherical radius on wrinkle are investigated by lots of numerical simulations, the outlines of spherical part with different thicknesses are extracted, and the maximum wrinkling value of spherical part with different forming temperatures and spherical radii are calculated. Then the multi-step multi-point thermoforming (MSMPTF) is chosen to depress wrinkle, and series of numerical simulations are put forward to get the forming step of non-wrinkle. Finally, MSMPTF experiment is done. Consequently, the spherical part has good outline shape, which illustrates that the MSMPTF technology is feasible to depress wrinkle.

## 1. Introduction

Resin sheet has characteristics of low density, high specific strength, excellent corrosion resistance, good ductility and insulation, which is used in aerospace, automobile, architecture, medical instruments and transport fields.

In the past two decades, flexible forming technology of resin sheet were studied by many researcher. The single point incremental forming method was carried out to form polymer sheet [1,2]. The flexible experimental machine with reconfigurable tooling and vacuum system was developed to form composite aircraft parts[3]. Multi-point thermoforming(MPTF) was used to form freeform panels[4]. MPTF machine was developed to study the feasibility and practicability of MPTF process[5,6].

Due to the flexible parameters of multi-point die manufacturing, MPTF technique has wide application prospects. Since the MPTF process of resin sheet is freeform, the wrinkle easily appears[7], which deteriorate the forming quality. Therefore, it is necessary to study the reason, influencing factor and elimination method of wrinkle to obtain good forming quality.

## 2. Numerical simulation and experiment of wrinkle

Polycarbonate (PC) sheet is selected as the objective material in this paper. According to series of tensile testing results for PC sheet, the following constitutive equation based on the generalized DSGZ model [8] is built to calculate stress-strain relation, and the model constants are listed in Table 1[6].



$$\sigma(\varepsilon, \dot{\varepsilon}, T) = K \left\{ f(\varepsilon) + \left[ \frac{\varepsilon e^{\frac{1-\varepsilon}{C_3 h(\dot{\varepsilon}, T)}}}{C_3 h(\dot{\varepsilon}, T)} - f(\varepsilon) \right] e^{(\ln(g(\dot{\varepsilon}, T)) - C_4) \varepsilon} \right\} h(\dot{\varepsilon}, T) \left( 1.25 - \frac{n}{1 + e^{\frac{-\varepsilon + s}{\delta}}} \right) \quad (1)$$

Where  $f(\varepsilon) = (e^{-C_1 \varepsilon} + \varepsilon^{C_2})(1 - e^{-a\varepsilon})$ ,  $h(\dot{\varepsilon}, T) = \dot{\varepsilon}^m e^{\frac{a}{T}}$ , and  $\dot{\varepsilon}$  is the strain rate.

Table 1. The material parameters of PC sheet

$C_1$	$C_2$	$m$	$a$	$K$	$C_3$	$\alpha$	$C_4$	$n$	$s$	$\delta$
2.87	0.42	0.075	5000	$1.64 \times 10^{-5}$	$2.79 \times 10^{-7}$	35	18.7	0.23	0.04	0.002

Numerical simulation on spherical part of resin sheet by MPTF process is carried out by ABAQUS software. Due to the symmetry, only a quarter of finite element model is set up, which is composed of multi-point die, elastic cushion and resin sheet, as shown in Fig.1. To save calculation time of CPU, multi-point die only retain the hemispheric end, which is simplified to rigid shell surface and meshed with three dimensional rigid and bilinear quadrilateral element R3D4. The thermostable silica is depicted with hexahedral solid element C3D8R. The PC sheet is modelled with quadrilateral shell element S4R. On the two symmetrical planes, the displacements normal to the planes and the rotations around the planes are constrained in the finite element models.

When the spherical radius is 300mm, the size of PC sheet is  $400 \times 400 \times 2$ mm, the forming temperature is  $150^\circ\text{C}$  and the forming pressure is 10000Pa. The numerical simulation result of wrinkle for spherical part is shown in Fig.2. It can be found that wrinkle appears in the four edges of spherical part obviously. MPTF experiment of PC sheet is carried out to verify the simulation result. Fig.3 shows the formed spherical part of PC sheet. The wrinkle also appears in four edges of spherical part, which is consistent with the simulated result. The reason is that the elastic modulus of PC sheet is very small at high-elastic state. PC sheet is easy to induce compressive instability during MPTF process without clamping device, which leads to local wrinkle. In order to acquire suitable forming parameters, it is necessary to study the influence factors and depressing method of wrinkle.

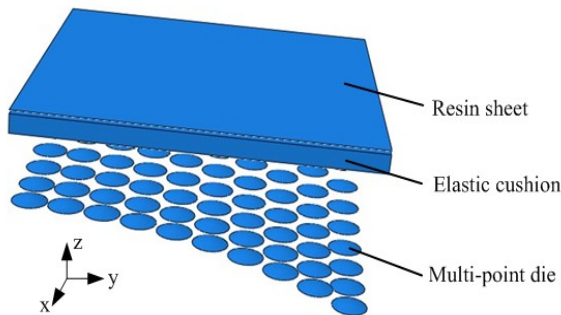


Figure 1. The FEM of MPTF for PC Sheet

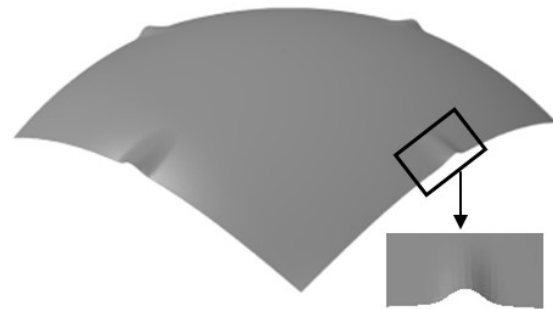


Figure 2. The wrinkle of spherical part

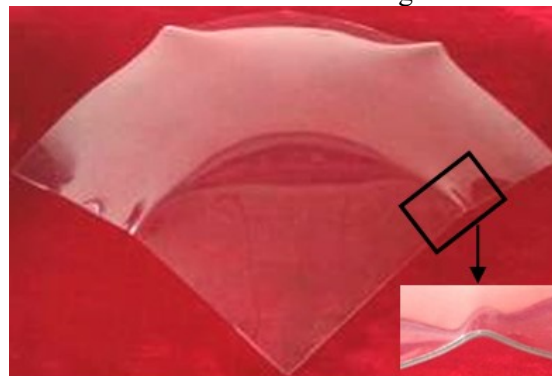


Figure 3. Wrinkle of spherical part formed by MPTF machine

### 3. The influencing factors and depressing method of wrinkle

#### 3.1. Influencing factors of wrinkle

The effects of thickness, forming temperature and spherical radius on wrinkle are simulated. The maximum wrinkling value is calculated by comparing the z coordinate of simulated and target part.

When forming temperature and spherical radius are 150°C and 300mm, separately. The z coordinate of line AC on spherical part with different thicknesses are shown in Fig.4. When the thickness is 1mm, the maximum wrinkling value is 13.72 mm. With the thickness increasing to 2mm, the maximum wrinkling value decreasing to 8.92mm. As the thickness coming to 4mm, wrinkle disappears on spherical part. It can be seen that the thickness affects the wrinkle significantly; the thicker the thickness is, the smaller the maximum wrinkling value will be.

When spherical radius is 300mm, the maximum wrinkling value of spherical part with different forming temperatures and thicknesses are shown in Fig.5(a). Obviously, the higher the forming temperature is, the larger the maximum wrinkling value will be. Taking the thickness of 3mm for example, the maximum wrinkling value is 5.06mm when the forming temperature is 150°C. With the forming temperature increasing to 165°C, the maximum wrinkling value comes to 8.31mm.

When forming temperatures is 150°C, the maximum wrinkling values of spherical part with different spherical radii and thicknesses are revealed in Fig.5(b). Obviously, the wrinkle appears on spherical part when thickness is 1mm, and the wrinkle disappears on spherical part when thickness is 4mm. Moreover, the maximum wrinkling value of spherical part decreases from 8.92mm to 0mm with the radius increases from 300mm to 500mm when the thickness is 2mm. Which indicates that the larger the spherical radius is, the smaller the maximum wrinkling value will be.

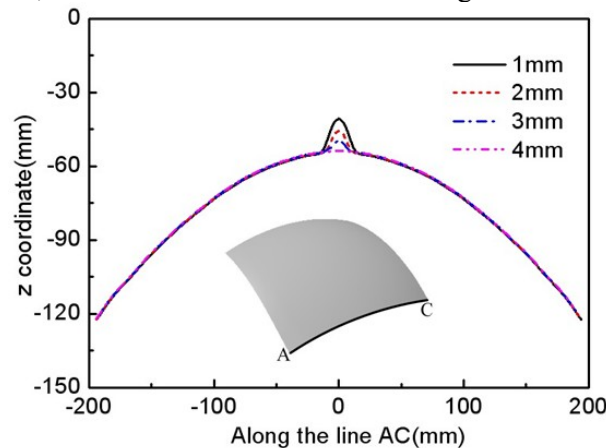


Figure 4. The z coordinate of spherical parts with different thicknesses

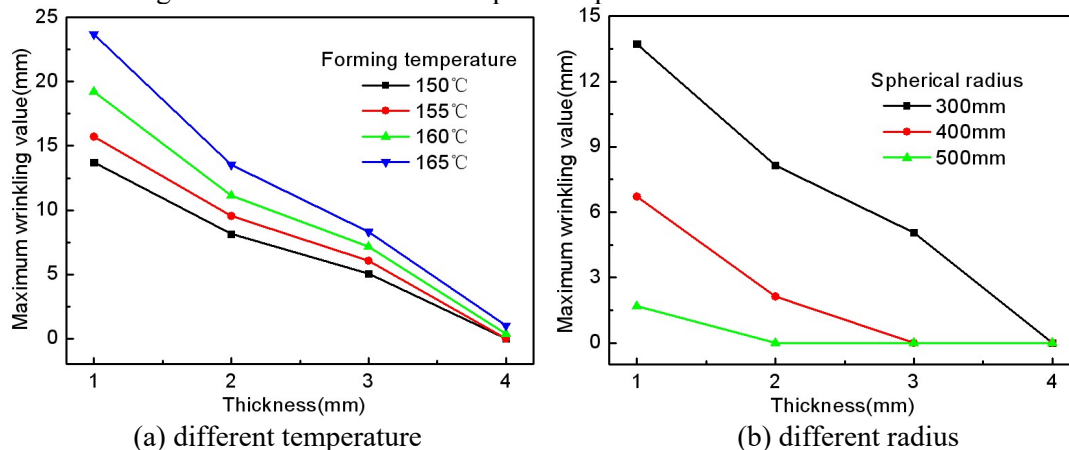


Figure 5. Maximum wrinkling value of MPTF with different forming parameters

### 3.2. Depressing of wrinkle

In order to depress the wrinkle, multi-step multi-point thermoforming (MSMPTF) is chosen to form PC sheet. The schematic diagrams of MSMPTF is shown in Fig.6.

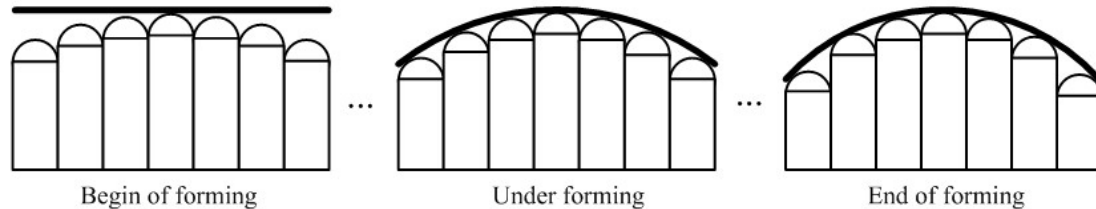


Figure 6. The schematic diagrams of MSMPTF

When spherical radius is 300mm and forming temperature is 150°C, the effect of forming step on the maximum wrinkling value with different thicknesses is shown in Fig.7(a). It can be found that the minimum thickness of non-wrinkle for spherical part with one step MPTF is 4mm. With the forming step increasing to three, the wrinkle disappears on spherical part with thickness of both 3mm and 4mm. When the forming step is five, the wrinkle disappears on spherical part with thickness of 1mm. Which illustrate that the thinner the thickness is, the more visible the effect of forming step on wrinkle will be.

Fig.7(b) shows the maximum wrinkling value of spherical part with different temperatures when spherical radius and sheet thickness are 300mm and 2mm, separately. Obviously, the more the forming step is, the smaller the maximum wrinkling value will be. Taking the forming temperature of 160°C as an example, the maximum wrinkling value of spherical part decrease from 11.23mm to 0.16mm when the forming step increase from one to five.

The maximum wrinkling values of MSMPTF with different spherical radii are shown in Fig.7(c) when forming temperature and thickness are 150°C and 1mm, respectively. It can be seen that three steps is necessary to depress the wrinkle when the spherical radius is 500mm. While the spherical radius is 400mm and 300mm, five steps is needed to eliminate the wrinkle on spherical part. The results show that the more the forming step is, the smaller the forming radius of spherical part without wrinkle will be.

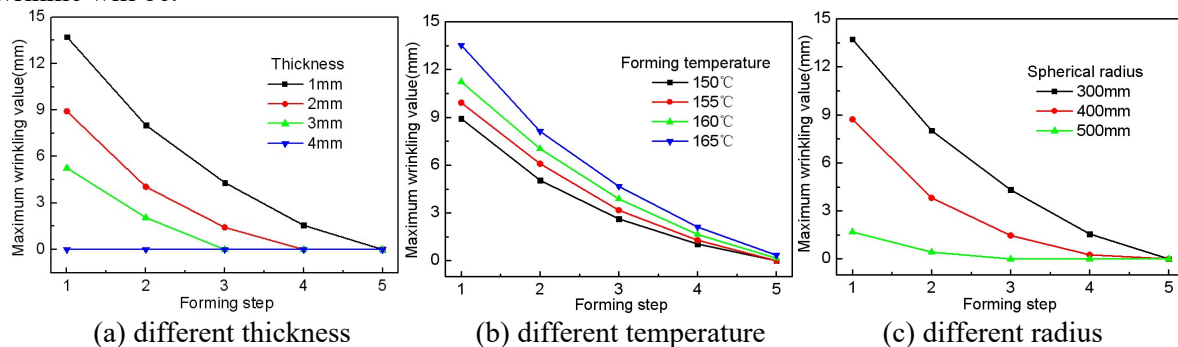


Figure 7. Maximum wrinkling value of MSMPTF with different forming situation

### 4. MSMPTF experiment of resin sheet

Combining the numerical simulation results, it can be found that the wrinkle is sensible to spherical radius, thickness, forming temperature and steps. So, the experimental conditions are set as follows: the spherical radius is 500mm, the thickness is 2mm, the forming temperature is 160°C and forming step is three. PC sheet is selected as the experimental material with size of 400×400mm, and thermostable silica is chosen as the elastic cushion with size of 400×400×20mm. The effective forming size of multi-point die is 400×400mm, punch number is 20×20 and punch radius is 20 mm. MSMPTF experiment of spherical part is done, as shown in Fig.8. Obviously, the spherical part has good profile shape, which verifies the MSMPTF technology is practical to form spherical part with large curvature.



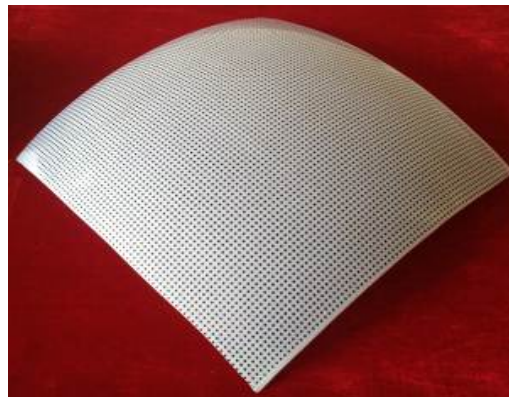


Figure 8. The experimental part of PC sheet with MSMPTF

## 5. Conclusions

The MPTF wrinkle of spherical part is simulated and verified. The effects of thickness, forming temperature and spherical radius on wrinkle are investigated by lots of numerical simulations. The results show that the higher the forming temperature is, the larger the maximum wrinkling value will be; the thicker the thickness or the larger the spherical radius is, the smaller the maximum wrinkling value will be. Then MSMPTF is chosen to eliminate wrinkle, and the effects of forming step on maximum wrinkling value of spherical part with different thicknesses, forming temperatures and spherical radius are simulated. The results show that the maximum wrinkling value can be decreased to zero by increasing the forming step. Based on the numerical results, the suitable forming parameters are acquired, and related experiment of MSMPTF for PC sheet is done. The results show that the spherical part has good profile shape, which confirms that the results obtained by numerical simulation are sensible and the MSMPTF method used to form spherical part with large curvature is practicable.

## Acknowledgements

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