

Numerical investigation of wrinkle for multi-point thermoforming of Polymethylmethacrylate sheet

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Abstract. The multi-point thermoforming (MPTF) machine and process of resin sheet were introduced, the glass transition temperature and stress relaxation curves of Polymethylmethacrylate (PMMA) sheet were tested, and the material parameters of PMMA sheet were got. Lots of numerical simulation of wrinkle for spherical part with MPTF of PMMA sheet were put forward, the effects of thickness, radius and forming temperature on the wrinkle were investigated, and the non-wrinkle forming limit diagram are determined. Then, MPTF experiments of spherical part with PMMA sheet was done to verify the numerical results. Consequently, the spherical part has good shape accuracy, which confirms that PMMA sheet formed by MPTF is feasible and the non-wrinkle forming limit diagram obtained by numerical simulation is practicable.

1. Introduction

Resin sheet has characters of low density, high specific strength, corrosion preventive, good ductility and good insulation, which is used in many fields, such as aerospace, automobile, architecture, medical instruments, transport and so on. There are three kinds of main forming methods for resin sheet, which are compression moulding, thermal diaphragm forming and bulging forming. All of these methods need specific mould, and it is hard to achieve multi-species, small batch and personal manufacture for its long manufacturing cycle and high cost, so it is urgent to demand flexible methods for forming resin sheet.

In the past two decades, considerable progresses have been made to study flexible forming technology of resin sheet. Gertner [1] proposed a rolling method to form polymer sheet after heating. Franzen [2] used single point incremental method to form the polymer sheet. Silva [3] and Martins [4] studied the single point incremental forming theory, optimized the forming process and carried out a series of experiments through polymer plate with good ductility. Walczyk [5] designed and developed flexible experimental machine by combining the reconfigurable tooling and vacuum thermoforming to form composite aircraft parts. Su [6] proposed the multi-point thermoforming to manufacture freeform panels by combining the multi-point forming and thermoforming. Peng [7] have developed multi-point thermoforming (MPTF) machine and studied the feasibility and practicability of MPTF.

Due to the manufacturing trends of individuation and flexibility for resin sheet, MPTF has broad application prospects. While the MPTF of resin sheet is freeform, and wrinkle is easily generated, which affect the forming quality. So, it is necessary to study the wrinkle and its influencing factors in order to obtain good profile shape.



2. MPTF Machine and Process

As is known, the resin sheet has three kinds of aggregate states, which are glassy state, high-elastic state and viscous flowing state. Generally, the resin sheet is formed at high-elastic state for good plasticity and ductility. Similar to sheet metal, the resin sheet can be formed by multi-point press forming or multi-point stretch forming, where the heating equipment is fabricate and the forming machine is expensive. So, the MPTF machine was developed by combining the single multi-point die and heating pressure box, as shown in Fig.1.

Fig.2 shows the MPTF process of resin sheet, which contain four steps. The first step: the shape of multi-point die was formed by calculating the height and adjusting the position of punch element based objective part. The second step: the resin sheet was placed above the multi-point die, heat was generated by lots of heating rods placed above the resin sheet until the temperature of resin sheet above its glass transition temperature, and the temperature is kept for several minutes. The third step: the compressed gas is pour into forming box through air pimp until the resin sheet accords fully with the multi-point die. The fourth step: the heating rods and air pump are closed, then the resin product is removed when it backs to room temperature.



FIGURE 1. MPTF Machine

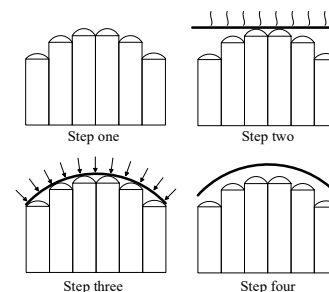


FIGURE 2. MPTF Process

3. Finite element simulation of MPTF for PMMA sheet

3.1 Material Parameters

PMMA is selected as the study object for its good comprehensive performance. The glass transition temperature of PMMA is measured as 105°C by dynamic mechanical analysis. The tests of stress relaxation are put forward in universal electronic testing machine, and the real stress relaxation curves of PMMA at different temperatures are shown in Fig.3.

Generalized Maxwell model can be selected to describe the viscoelastic behaviour of resin sheet, its relaxation property can be described by Prony series in ABAQUS, and the Prony series of generalized Maxwell model can be expressed by the following equation:

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

Where e_i and τ_i are coefficients of Prony equation.

The coefficients of Prony equation for PMMA are listed in Table1. The effects of temperature and time on the mechanical properties of PMMA sheet can be transformed into each other under certain conditions based on equivalent conversion principle of time and temperature, which indicate that the viscoelastic behaviour of resin sheet in different temperature can be forecasted by displacement factor. The displacement factor is the function of temperature, and it can be calculate by the Williams-Landel-Ferry (WLF) [8] given by the eq.2.

TABLE 1. Material parameters of PMMA

parameter	i_1	i_2	i_3	i_4	i_5
e_i	0.2788	0.1589	0.2729	0.2506	0.0403
τ_i	0.0136	0.1049	1.3188	11.379	569.62

$$\lg a_T = -\frac{C_1(T-T_0)}{C_2+(T-T_0)} \quad (2)$$

Where C_1 and C_2 are the constant, T_0 is the reference temperature, T is the objective temperature, and the a_T is displacement factor, which can be expressed by the eq.3.

$$a_T = \frac{\tau}{\tau_0} \quad (3)$$

Where τ and τ_0 represent the time of stress relaxation when the temperature of T and T_0 , respectively. The constants of C_1 and C_2 for PMMA sheet are 6.71 and 65.01, respectively.

3.2 Finite Element Model

Numerical simulation of MPTF for PMMA sheet is carried out by ABAQUS. Spherical part is selected as the objective shape of formed part. Due to the symmetry, only a quarter of finite element model is analysed, as shown in the Fig.4. The FEM is composed of multi-point die, elastic cushion and resin sheet. The size of multi-point die is 400×400mm, punch number is 20×20 and punch radius is 20 mm. To save computing time of CPU, multi-point die only retain the hemispheric end; it is simplified to rigid shell surface and modelled with bilinear quadrilateral three dimensional rigid element R3D4. The thermostable silica is selected as the elastic cushion, its size is 400×400×20mm, and it is modeled with hexahedral solid element C3D8R. The resin sheet is modeled with quadrilateral shell element S4R. Effective hourglass control techniques are used to avoid the spurious deformation modes during finite element simulations. On the two symmetrical planes, the displacements normal to the planes and the rotations around the planes are constrained in the finite element simulations.

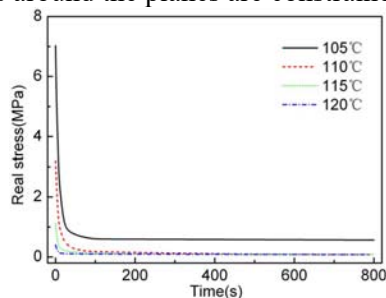


FIGURE 3. Stress relaxation curves of PMMA

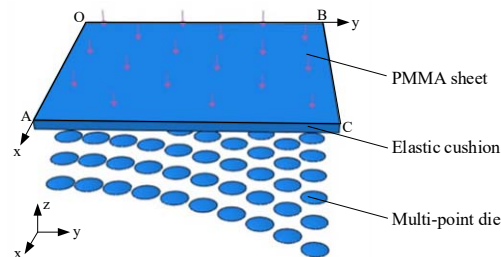


FIGURE 4. The FEM of MPTF for PMMA sheet

4. Numerical simulation of wrinkle in MPTF of PMMA sheet

When the radius of spherical part is 300mm, the forming is 110°C, four kinds of thicknesses are investigated. The z coordinate of line AC on spherical part with different thicknesses is shown in Fig.5(a). When the thickness is 1mm, the maximum value of wrinkle is 9.3mm. With the thickness increase to 2mm, the maximum value of wrinkle decreases to 5.4mm. When the thickness increases to 4mm, no wrinkles appear in spherical part. It can be found that the thicker the thickness is, the smaller the wrinkle will be for resin sheet.

When the thickness of PMMA sheet is 2mm, the forming temperature is 110°C, three kinds of radii are investigated. Fig.5(b) shows the z coordinate of line AC on spherical part with different radii. The following features can be found: the larger the forming radius is, the smaller the wrinkle will be. These results illustrate that the larger the forming radius is, the smaller the wrinkle will be, since a smaller forming radius leads to a larger deformation.

Fig.5(c) presents the z coordinate of line AC on spherical part with different forming temperatures when the thickness of resin sheet is 2mm and forming radius is 500mm. Obviously, there is no wrinkle on spherical part when the forming temperature is 110°C. With the forming temperature increase, the maximum wrinkling values of spherical part are 1.0mm and 3.1mm when the temperature are 115°C and 120°C respectively. These results illustrate that the higher the forming temperature is, the larger the average shape error will be. Because a higher forming temperature leads to a more soft resin sheet, which leads to a larger value of wrinkle.

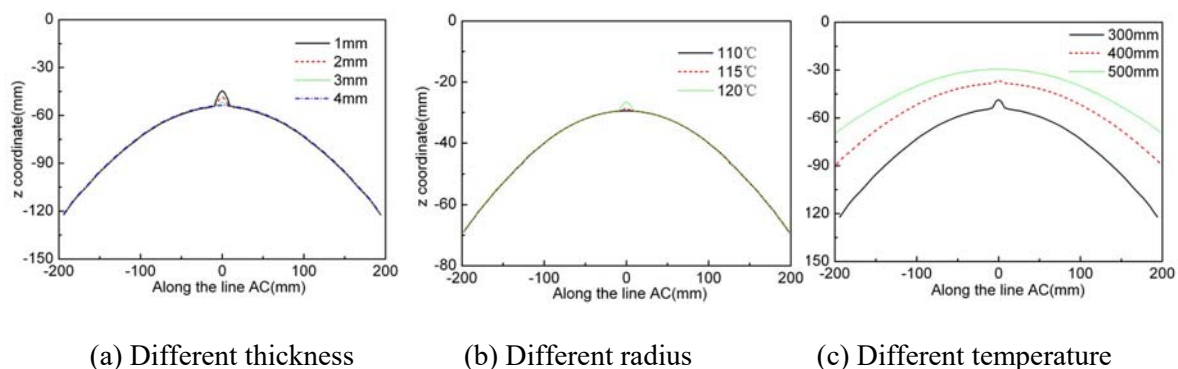


FIGURE 5. The z coordinate of spherical parts along the line AC with different forming parameters

The wrinkle of spherical part with MPTF of resin sheet is influenced by many factors such as the thickness, radius and temperature. It is difficult to control wrinkling by considering all of these complex factors. However, the limit curves of spherical part without wrinkle are beneficial for choosing forming parameters, which can be got by lots of numerical simulation and computations. When the size of multi-point die is 400×400mm, punch number is 20×20 and punch radius is 20 mm, the non-wrinkle forming limit curves of spherical parts are shown as Fig.6, which are plotted by getting the minimum radius of spherical when the temperature and thickness are fixed. The increasing amplitude spherical radius is chosen as 50mm in order to save computing time. It can be seen that if the radius above the limit curve, the spherical part can be formed well.

5. MPTF experiment of spherical part

The forming experiment of spherical part is carried out in the MPTF machine. The effective forming size of multi-point die is 400×400mm, punch number is 20×20 and punch radius is 20 mm. The experimental conditions are set as follows: the size of PMMA sheet is 400×400×2 mm, spherical radius is 500mm and the forming temperature is 110 °C. Fig.7 shows the experimental photo of spherical part with MPTF of PMMA sheet. It can be found that the spherical part has good profile shape and no wrinkle appear, which verifies the correction of numerical results.

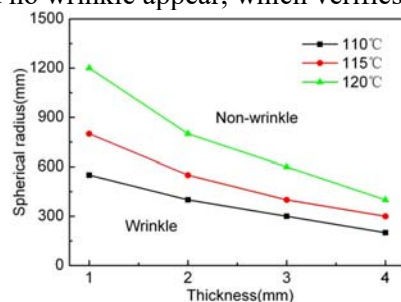


FIGURE 6. The non-wrinkle forming limit

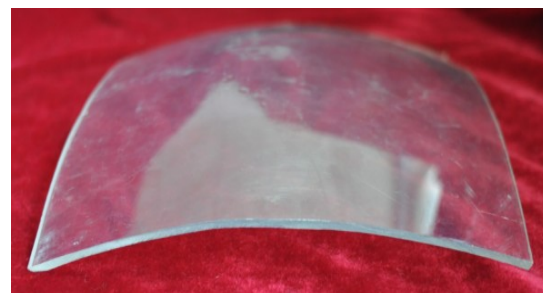


FIGURE 7. The photo of spherical part with MPTF

6. Conclusions

The machine and process of MPTF for resin sheet were introduced, and the material parameters of PMMA sheet were got. Numerical simulations are carried out to investigate the effects of thickness, radius and temperature on the MPTF of PMMA sheet. The results show that the thicker the sheet thickness or the larger the forming radius or the lower the forming temperature, the smaller the wrinkle will be. The non-wrinkle limit diagrams of spherical part with MPTF of PMMA sheet are got by lots of numerical simulations, and then the MPTF experiment is done. The result shows that the spherical part has no wrinkle and good surface quality, which illustrate that the MPTF of PMMA sheet is feasible and the forming limit diagram is practical.

Acknowledgments

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