Aero2015P791T4

The 14th International Conference of Iranian Aerospace Society
Communication and Space Technology, Iranian Research Organization for Science and Technology, Tehran, 3th to 5th of March, 2015.

The 14th International Conference of Iranian Aerospace Society

Mechanical Model of PMMA in Thermoforming Process Simulation

Majid Rezaei[1], Kourosh Hasanpour[2]

Isfahan, University of Isfahan, Faculty of Engineering, Group of Mechanical Engineering

Abstract

Thermoforming, as a common and simple method of forming polymeric parts, is a deformation process of a polymer in the rubbery state above its glass transition temperature. However the contact of the softened polymeric sheets with the die surface at different stages of thermoforming can affect the final geometry of the component.

Poly metal methacrylate (PMMA) is a type of polymer with many industrial applications such as manufacturing airplane canopy bubble which is carried out at high temperature (130ºC). It is ideally processed slightly above its glass transition temperature and at low strain rates to limit optical distortions. An accurate model is needed to describe the polymer behavior in numerical simulations to reliably predict the resulting shape and provide industry with inexpensive and fast tool design.

The behavior of PMMA is highly nonlinear and depends on the temperature, so simulation of its forming process is a useful solution to verify the effect of relevant parameters using FEM. Process simulation requires an appropriate mechanical behavior for PMMA. In this paper, different mechanical behaviors of PMMA are used to simulate the canopy bubble forming process. First, four simulations with elastic-plastic model, Mooney-Rivlin, Ogden and polynomial are done by Abaqus/Implicit. Then, two cross sections are demonstrated in two perpendicular path samples through final shapes. Finally section profiles are compared with experimental profile and an appropriate mechanical behavior for PMMA in high temperature forming processes is suggested.

Keywords: *PMMA forming- FEM simulation- mechanical behaviors- airplane canopy*

Introduction

Polymers show different behaviors in forming processes depend on their properties. These behaviors have effects on final product shape, forming process and maybe the time and cost of process [1]. So the study and investigation on the behavior of materials and forecasting their behavior in forming process is important and effective.

On the other hand forming processes simulation in a finite element analyses program such as ABAQUS or ANSYS helps to predict final shape of material and obtain more accurate forming parameters [2].

PMMA is a thermoplastic polymer with an amorphous structure usually available in the form of plates or bars. Its various engineering applications are met in aeronautics, nuclear industry, machinery equipment and protective structure against shocks or ballistic impacts. It has been made appealing by its relative low density and its transparency as well [3].

PMMA is an expensive polymer used in aircraft industry. It's used to produce the canopy bubble. The initial material is produced in different shapes and sizes such as rectangular sheets and in a range of various thicknesses. After forming, PMMA sheet is shaped as a bubble [4].

There are different ways to form PMMA sheet such as free forming, plug assistance, etc. [5]. In every forming process, simulation in a FEM program is a helpful task to predict mechanical behavior of PMMA. In other words, selecting an appropriate behavior for PMMA in a forming process simulation helps to close up FEM results to experimental ones. For FEM simulations of thermoforming polymeric materials, hyper elastic and elastic-plastic models are the two commonly used rheological models [6].

In this paper it is tried to simulate canopy bubble forming process at 130ºC using different mechanical behaviors for PMMA using various models described above. Then FEM results compared with experimental ones and the accuracy of results is investigated.

Mechanical properties of PMMA

Poly methyl methacrylate is the polymer of methyl methacrylate, with chemical formula $C_5H_8O_2)_n$. It is a clear, colorless polymer available on the market in both pellet and sheet form under the names Plexiglas, Acrylate, Perspex, Plazcryl, Acrylplast, Altuglas, Lucite etc. It is commonly called acrylic glass or simply acrylic [7].

It is produced by free-radical polymerization of methyl methacrylate in mass (when it is in sheet form) or suspension polymerization according to figure 1:

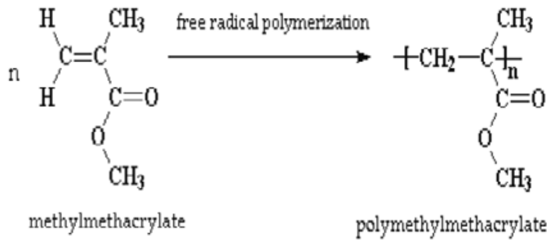

Figure 1- Free-radical polymerization of methyl-methacrylate to produce PMMA [7]

1. MSc. Student
2. Assistant Professor, 0098-03137934021, hasanpur@eng.ui.ac.ir

PMMA is a transparent thermoplastic polymer known as organic glass. From the mechanical properties aspect, this polymer is used because of the higher impact resistance and better formability in comparison with ordinary glass [5]. PMMA has high mechanical strength and low elongation at break. It does not shatter on rupture. It is one of the hardest thermoplastics and is also highly scratch resistant. It exhibits low moisture and water absorbing capacity, due to which products made have good dimensional stability. Table 1 shows mechanical characteristics of PMMA. The mechanical properties of PMMA change as a result of temperature variations, same as some other thermoplastics.

The thermal stability of standard PMMA is under 70º C, but under special conditions, e.g., pressure, it can withstand stable up to 100º C [8]. PMMA is a combustible material, which continues burning even after the flame is removed. Table 2 shows thermal characteristics of PMMA.

Table 1- Mechanical properties of PMMA

Number	Mechanical Properties	Value
1	Density	1.15 - 1.19 g/cm3
2	Young Modulus	20 MPa
3	Water Absorption	0.3 – 2 %
4	Hardness, Rockwell M	63 - 97
5	Tensile Strength, Ultimate	47 - 79 MPa
6	Elongation at Break	1 - 30 %
7	Tensile Modulus	2.2 - 3.8 GPa

Table 2- Thermal properties of PMMA

Number	Thermal Properties	Value
1	Specific Heat Capacity	1.46 - 1.47 J/g.°C
2	Thermal Conductivity	0.19 - 0.24 W/m.K
3	Melting Point	140ºC
4	Glass Temperature	100 - 105 °C
5	Maximum Service Temperature, Air	41-103 °C

Thermoforming process

Thermoforming is a manufacturing process used to form polymeric sheet into complex three-dimensional shape. In other words, the main feature of the thermoforming process is to form flat polymer sheet which is clamped around its edge into 3D shape. The temperature of a previously extruded thermoplastic sheet is raised far above the glass transition temperature of the specific resin system to deform the material to the desired shape using a differential pressure and a male or female die [5].

In the thermoforming process, the quality of the final part is greatly dependent on the material flow and the resulting thickness distribution. The traditional “trial and error” method used for optimizing these manufacturing processes, as done today, is quit time-consuming and expensive, and hence numerical simulation has been introduced as a powerful tool for process optimization to avoid the waste of resources [6].

Different kinds of the thermoforming process have been developed in the past years, such as vacuum forming, drape forming, inverse drape forming, drape forming reverse, blow forming with or without plug assistance, blow up reverse, vacuum reverse, blow up vacuum reverse, skin pack, blister ball packaging, and continuous cycling. The vacuum and plug-assisted forming processes are depicted in figures 2-(a) and 2-(b) respectively.

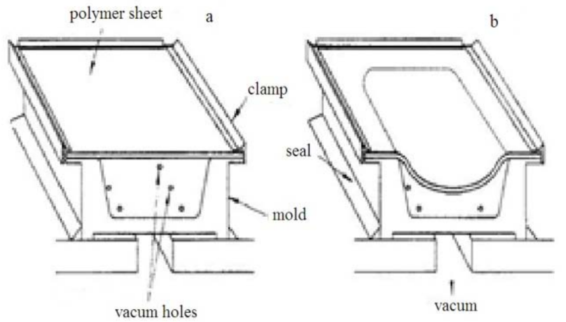

Figure 2- Vacuum forming: (a) preheated clamped sheet over female mold prior to forming; (b) vacuum applied [9].

Free forming (which is also known as “Bubble Inflation”) is a kind of thermoforming processes in which the sheet is clamped between two holders and air pressure causes the heated sheet to inflate freely to form the desired shape which is mostly appropriate for symmetrical parts. The main problem with this method is that the sheet almost undergoes thinning from the edges to the center, so that the thickness is minimum in the center. Practically this phenomena causes the parts tear during forming process or have lower mechanical properties. The schematic of this process is illustrated in Figure 3.

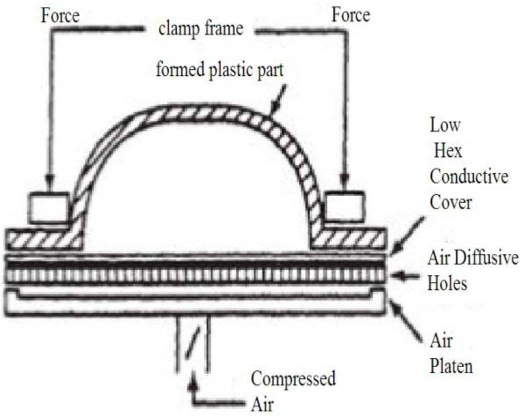

Figure 3-Free forming schematic [5]

A detailed description of thermoforming operations, equipment design as well as heating and cooling issues is described by Throne [10].

Canopy bubble forming process

In the production of canopy bubble which surveyed in this paper, a PMMA sheet in a trapezoidal shape with the thickness of 20mm is putted on the die. This model of canopy bubble is produced in a free-forming process and dies have contact with sheet just at boundaries.

First, the PMMA sheet is putted on lower die in a flat state. The set is in an oven. Then the oven temperature increased from room temperature to 130ºC within two hours. Simultaneously through warming oven and set, sheet goes to pasty state and lies on the lower die. After that upper die is putted on sheet and the sheet boundary is clamped between two dies.

Then air pressure is applied to the lower side of sheet with an amount of 0.2 bar and sheet is inflated up to a certain height. Next, pressure decreases to 0.1 bar and sheet height shrinks. Determining the time of loading the arbitrary height could be achieved. Then sheet stays in this state some minutes and after that it starts to cool slowly.

As said before, the thickness of sheet is minimum in the center.

Simulation of Process in Abaqus

Canopy bubble forming process with PMMA sheet is simulated in Abaqus as explained before. Different mechanical behaviors for PMMA are used in the simulation. Then results are compared with experimental one.

To do this, the stress-strain diagrams in both room-temperature and 130ºC are required. So the uniaxial tension tests are done at two required temperatures and stress-strain results are obtained. Different mechanical behaviors (such as Ogden, Mooney-Rivlin, etc.) for material can be defined in ABAQUS using experimental test results.

Diagrams in Figures 4 and 5 depict uniaxial tensile test of PMMA at two above mentioned temperatures. Figure 6 shows the test setup and specimen.

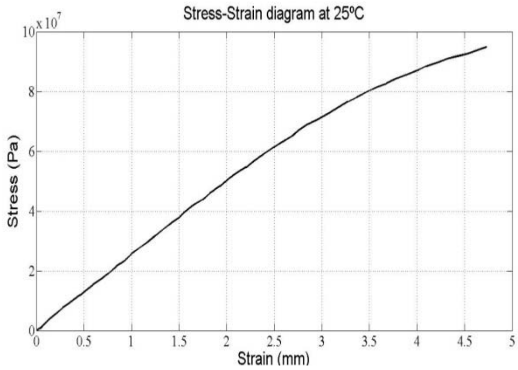

Figure 4- Stress-strain diagram of PMMA at 25ºC

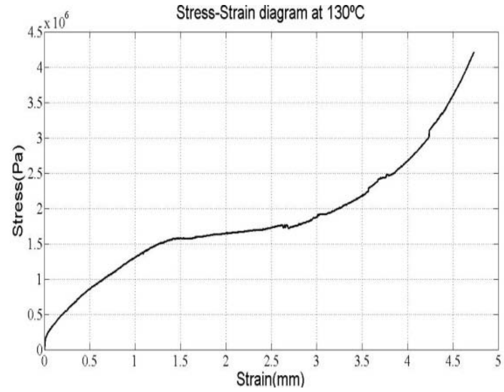

Figure 5- Stress-strain diagram of PMMA at 130ºC

(a) (b)

Figure 6- Tensile test set (a) - Tensile test specimen (b)

Stress-strain values were used to define material properties in program. In Abaqus/CAE, four simulations were performed with Standard/Implicit which in every simulation, the behavior of material was different from the others. Elastic-plastic model, Mooney-Rivlin, Ogden and polynomial were compared with each other. Hyperelastic model equations are represented in Table 3 where W is strain energy density function. All coefficients in equations bellow extracted from uniaxial test results and were evaluated by Abaqus. Result of forming in Abaqus with elastic-plastic model is shown in Figure 7.

Table 3- Hyper elastic models equations [7]

number	Hyper elastic model	equation
1	Mooney-Rivlin	$W = C_1(\bar{I}_1 - 3) + C_2(\bar{I}_2 - 3)$
2	Ogden	$W(\lambda_1,\lambda_2) = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p}(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_1^{-\alpha_p}\lambda_2^{-\alpha_p} - 3)$
3	polynomial	$W = \sum_{i,j=0}^{N} C_{ij}\,(I_1 - 3)^i\,(I_2 - 3)^j \; ; C_{00} = 0$

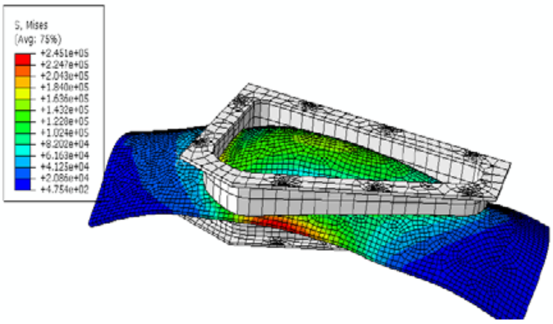

Figure 7- Elastic-plastic model of PMMA simulated analyzed in Abaqus

According to experimental canopy bubble's height and shape, the comparison between different material behaviors can be done and an appropriate mechanical behavior for PMMA in forming at high temperatures like 130ºC can be chosen.

Results and discussions

To identify the most similar behavior to PMMA, in each shape obtained from Abaqus, two cross sections are demonstrated in perpendicular path as shown in Figures 8 and 9. The cross sections are passed through the maximum height.

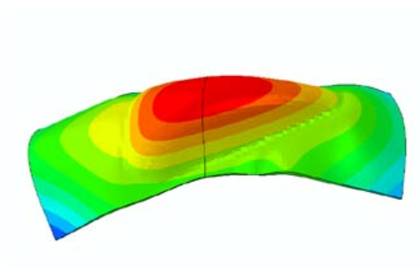

Figure8-Transverse cross section

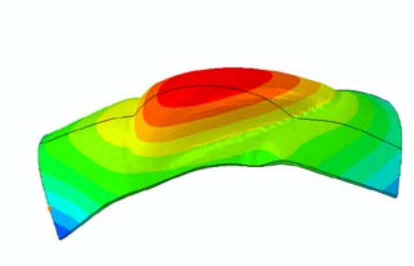

Figure 9-Longitudinal cross section

Cross section profiles are compared with experimental one in Figures 10 and 11. According to profile diagrams, the closest profile to experimental one is profile of elastic-plastic model.

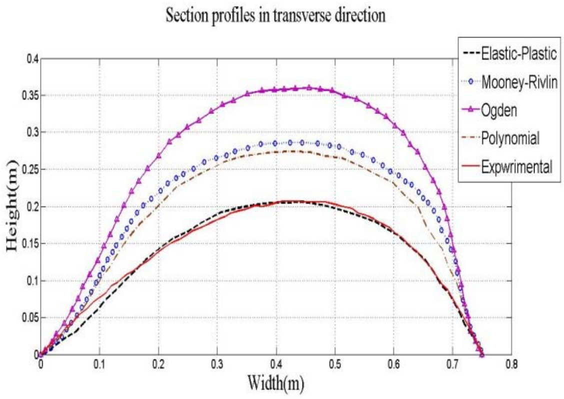

Figure 10- Section profiles in transverse path

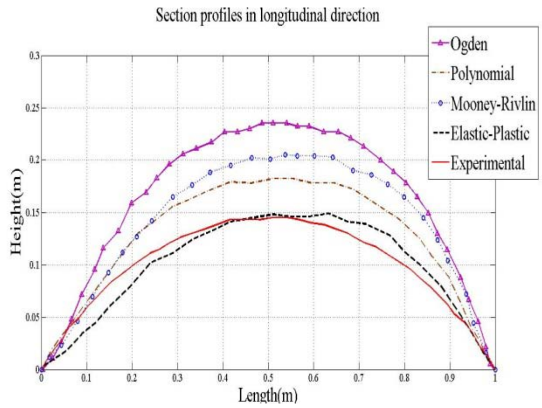

Figure 11- Section profiles in longitudinal path

Conclusion

According to obtained results, at high temperature forming process (130 ºC), elastic-plastic model has more conformity with real behavior of PMMA than the others. Due to the plastic deformations and return amount of sheet height after pressure decreasing, the hyperelastic models cannot illustrate the material behavior at that temperature as is. In other words they can't express the plastic deformations so good.

References

1- O'Connor C.P.J., Menary G., Martin P.J. and McConville E., Finite element analysis of the thermoforming of Polypropylene, 1(1), Apr, 2008, pp.779-782.

2- Dong Y. and Lin R.J.T. and Bhattacharyya D., Finite Element Simulation on Thermoforming Acrylic Sheets Using Dynamic Explicit Method, *Centre for Advanced Composite Materials (CACM)*, 14(3), Sep, 2006.

3- Nasraoui M., Forquin P., Siad L., Rusinek A. and Dossou E., Mechanical behaviour of PMMA: Influence of temperature and confining pressure, *9th International Conference on the Mechanical and Physical Behaviour of Materials under Dynamic Loading (DYMAT 2009)*, Vol.2, sep.15, 2009, pp. 1103-1108.

4- Labra John J., Finite-Element Modeling of a Fighter Aircraft Canopy Acrylic Panel, *Journal of Aircraft*, 19(6), June, 1982, pp.480-484.

5- Amiri E., A Finite Element Investigation on Thickness Distribution of PMMA Sheets in a Combination of Free

Forming and Plug Assistance Forming, *17th Annual (International) Conference on Mechanical Engineering-ISME*, University of Tehran, Iran, 2009.

6- Dong Y., Lin R. J. T. and Bhattacharyya D., Determination of critical material parameters for numerical simulation of acrylic sheet forming, *Journal of Materials Science,* Vol.40**.** 2005, pp. 399– 410.

7- http://en.wikipedia.org/wiki_ (hyper elastic model)**.**

8- R´egnier G., Gilormini, P. and Chevalier, L., Thermoforming poly (methyl methacrylate) transparencies, *Society of Plastics Engineers (SPE)*, 2010.

9- Carlone P. and Palazzo G.S., Finite Element Analysis of the Thermoforming Manufacturing Process Using the Hyper elastic Mooney-Rivlin Model, *International Conference on Computational Science and Its Applications (ICCSA)*, 3980, 2006., pp. 794-803.

10- Throne J.L., *Thermoforming*, Hanser Publishers, 1st Ed. New York, 1987.