Int J Adv Manuf Technol (2002) 20:230–235
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The International Journal of
Advanced
Manufacturing
Technology

The Characterisation and Finite-Element Analysis of a Polymer under Hot Pressing

C.-R. Lin, R.-H. Chen and C. Hung
Department of Mechanical Engineering, National Chiao-Tung University, Hsinchu, Taiwan

Finite-element simulation of the hot pressing process has been performed using ABAQUS. The viscoelastic polymer (polymethyl methacrylate) used in this study has mechanical properties that depend on the temperature and working pressure. Based on the nonlinear viscoelastic model, the polymer material behaviour is simulated successfully with the data obtained from material tests. Simulation results conform to related experiments, indicating that the approach can accurately predict pressure distribution within a polymer hot pressing.

Keywords: Finite-element method; Hot pressing; Nonlinear viscoelastic; Polymer

Introduction

Polymer products are being greatly used around the world. Plastic and rubber are the two main categories of polymers which are composed of numerous long-chain state molecules. Most plastic products, excluding large ones, are manufactured by the injection moulding method. The hot pressing method (Fig. 1) is an effective means of manufacturing larger plastic products. The fine structure elements used in micro electro mechanical systems (MEMS) are manufactured via the LIGA process. The final procedure in the LIGA process, i.e. micromoulding, generally incorporates the hot pressing method.

There have been some studies on simulating polymer material properties by FEM. These investigations can be characterised into two groups:

1. Schmidt and Carley [1] and Day [2] et al. used the hyperelastic model to simulate polymer material properties in the semi-molten state. They indicated that in semi-molten state ($T_g < T < T_g + 60$, where T_g is the glass transition temperature) some amorphous polymers had rubber-like properties. Typically, rubber is a nonlinear elastic material.

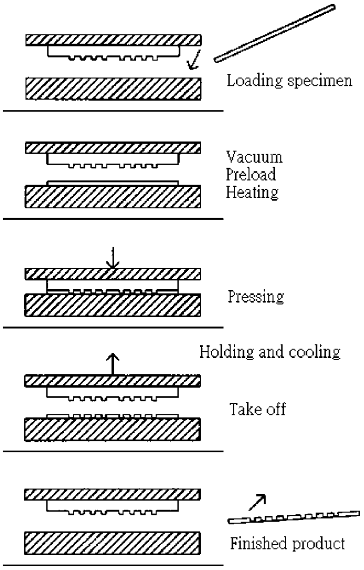

Fig. 1. Hot pressing method.

2. Krishnaswamy et al. [3,4] used viscoelastic or viscoplastic models to simulate the material properties of a ductile crystalline polymer, such as polyethylene (PE), at room temperature. These papers indicated that the linear viscoelastic model is suitable for approximating the mechanical response of the material under low stress levels and short loading times, whereas the nonlinear viscoelastic model can approximate the material behaviour at high stresses and long loading times.

Polymethyl methacrylate (PMMA) used in this study is an amorphous polymer material that has nonlinear viscoelastic material properties. In principle, the combinations of springs (express elastic) and dashpots (express viscous) can simulate the viscoelastic model. For example, the Maxwell model [5] (Fig. 2(*a*)) uses the series of one spring and one dashpot to express the viscoelastic model. This model is excellent for simulating the polymer's stress relaxation phenomenon, but is inappropriate for simulating the creep characteristic. Alternatively, the Kelvin model [5] (Fig. 2(*b*)) juxtaposes one spring

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Correspondence and offprint requests to: Professor C. Hung, Department of Mechanical Engineering, National Chiao-Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan. E-mail: chhung@cc.nctu.edu.tw

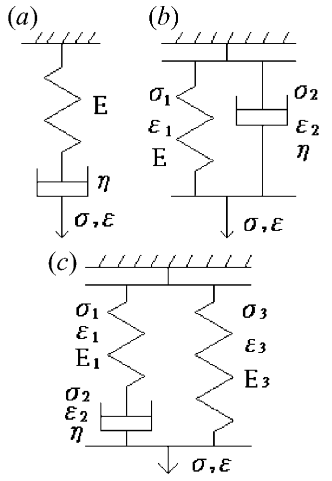

Fig. 2. (*a*) Maxwell model, (*b*) Kelvin model, and (*c*) three-elements solid model.

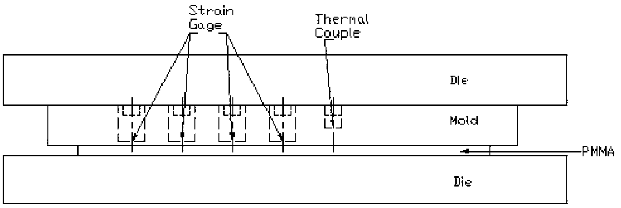

Fig. 3. Surface pressure measurement set-up.

and one dashpot to simulate the viscoelastic model. This model can simulate the polymer's creep phenomenon, but is not suitable for simulating the stress relaxation characteristic. The three-element solid model [5] (Fig. 2(*c*)) simulates the viscoelastic model by a spring juxtaposed with a series of a spring and a dashpot. This model can express both the creep and stress relaxation characteristics of the materials and, thus, it is the preferred viscoelastic model for our purposes.

This study demonstrates that, in semi-molten state, PMMA exhibits nonlinear elastic characteristics and that, during the hot pressing process, the time effect is significant. Consequently, a suitable three-element solid model was adopted in the finite-element method (FEM) to express the nonlinear viscoelastic material behaviour of PMMA completely. For checking the validity of the FEM approach, surface pressure distribution measurements under constant pressure and temperature were performed.

2. Material Tests and FEM Simulation

2.1. Material Experiments

Casting PMMA material made by CHI-MEI Co. was employed in this study. Its Young's modulus, thermo-conductivity coefficient and viscosity are dependent on temperature, pressure, and working time. To obtain the required material parameters under simulation, uniaxial compression experiments at various temperatures and creep tests were executed.

2.1.1 Uniaxial Compression Test

PMMA specimens were compressed at various temperatures to obtain the stress/strain relationship. The experimental apparatus included a material test machine (MTS 810) and a high-temperature furnace. Table 1 gives the specifications of specimens and test parameters, which were referred to ASTM D695 [6].

During the tests, the temperature variation was controlled within ±2°C. From this experiment, the stress/strain relationships of PMMA at various temperatures were obtained, which can be used in the finite-element analysis to approximate the nonlinear elastic characteristics of the material.

2.1.2 Creep Test

Usually, a polymer material has a significant creep phenomenon, especially at higher temperatures. To obtain the time effect of the PMMA during the hot pressing process, a creep test was conducted using a cone and plate viscometer. The diameter and thickness of the samples were 25.4 mm and 1.8 mm, respectively. The sample, heated to 160°C, was placed under a fixed shear stress, 1000 Pa, during which its shear strain, which varied with time, was measured. The test duration was 900 s. The stress relaxation modulus, calculated from shear stress and shear strain, was incorporated into the FEM to approximate the time effects of the material.

2.2 PVT Characteristics

The pressure-specific volume–temperature (PVT) relationship is another important characteristic of the polymer during forming. The specific volume is the inverse of the density. With a constant mass, a change in specific volume means a change in volume. If the volume varies with temperature and/or pressure, it causes different contractions at different areas of the material.

Specific volumes at pressures of 0.1, 30, 60, and 90 MPa, with respect to temperatures of 40°C–270°C, were measured using a PVT-100 machine.

2.3 Finite-Element Simulation

In the finite-element analysis, the ABAQUS/standard code was used to perform the simulation. The VISCOELASTIC and HYPERELASTIC commands were applied to characterise the nonlinear viscoelastic behaviour of the PMMA. The large strain

Table 1. Experimental conditions of uniaxial compression.

	Data	
Specimen	Diameter (mm)	12.7
	Length (mm)	25.4
Experimental conditions	Speed (mm min^{-1})	1.2
	Displacement (mm)	8
	Temperature range (°C)	50–170
	Temperature increment (°C)	10

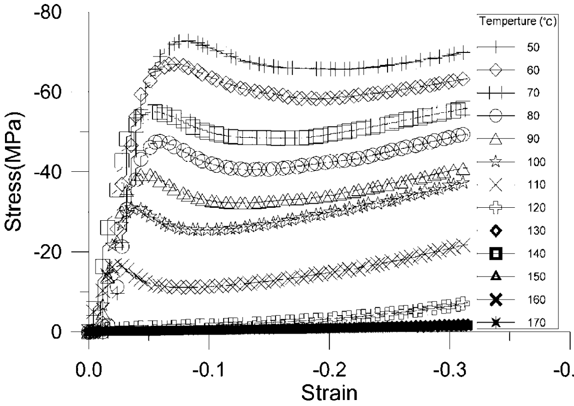

Fig. 4. Stress–strain relationships.

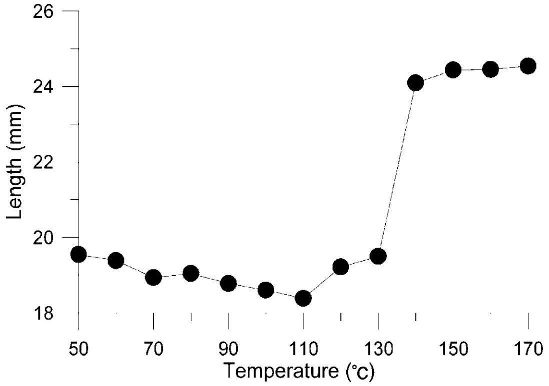

Fig. 5. Final length.

incompressible nonlinear HYPERELASTIC command that equalled the stress/strain data from the compression test was used to specify the short-term elastic properties, i.e. to handle the instantaneous displacement behaviour of the PMMA during the situation of loading and unloading. Similarly, the VISCO-ELASTIC command that equalled the shear stress relaxation modulus from the creep test was used to specify the time-dependent behaviour of PMMA. The isothermal and geometric nonlinearity conditions were used in the following simulation cases. All dies were regarded as rigid bodies and the frictional boundary condition was set to rough, that is, no sliding occurs between the dies and the workpiece.

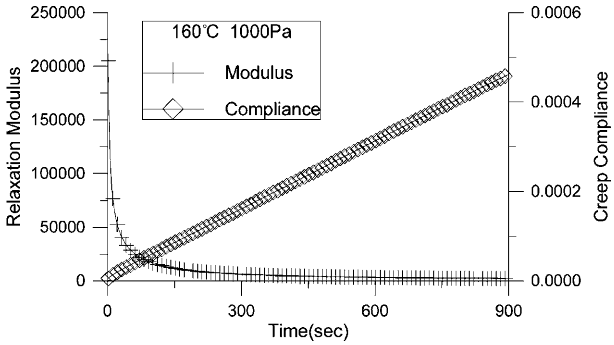

Fig. 6. Creep compliance–relaxation modulus–time relationship.

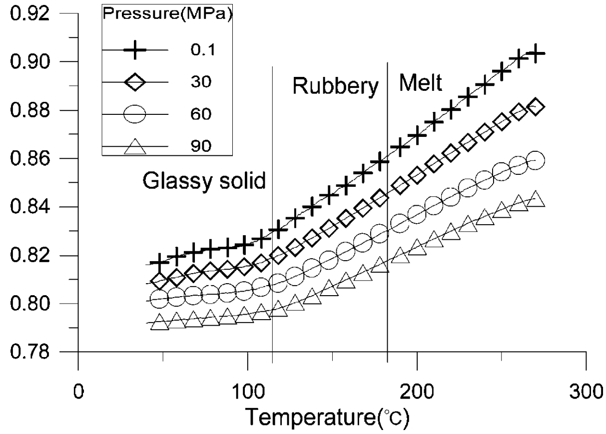

Fig. 7. PVT relationship of PMMA.

FEM analysis was employed to simulate the surface pressure distribution of the specimen during hot pressing. Table 2 presents the simulation conditions, for which a total of 2200 CAX4H elements (the quadratic, axisymmetric, and hybrid continuum elements) were employed. The load with a time period of 1 s was applied in the first step, so that the instantaneous behaviour is dominant. For the second step, to express the time-dependent behaviour of PMMA, the load was held constant for three distinct time periods, 100, 200, and 300 s.

2.4 Pressure Distribution Measurements

To verify the validity of the FEM simulation, the surface pressure distribution measurement that was originally designed by Lai [7] was conducted. The experimental conditions were the same as those indicated in Table 2. Figure 3 illustrates the design of the surface pressure measurement.

3. Results and Discussions

3.1 Compression Test

Figure 4 shows the stress–strain relationships of the PMMA at temperatures of 50°C–170°C. Clearly, the PMMA displays elastic-plastic behaviour below 120°C and viscoelastic behaviour when the temperature exceeds 120°C, i.e. the PMMA retains a solid state until the temperature reaches 120°C and then it transforms to a semi-molten state. Consequently, the glass transition temperature was 110°C–120°C. Compared with

Table 2. Simulation conditions for pressure distribution.

	Data	
Specimen	Diameter (mm)	110
	Thickness (mm)	2
Simulation conditions	Load (N)	75 194, 112 791
	Temperature (°C)	160
	Time period (s)	1, 100, 200, 300
	Measured position (mm)	$r = 0, 15, 30, 45$

the definition of the amorphous polymer's semi-molten temperature ($T_g < T < T_g + 60$), 160°C may be a preferred working temperature for PMMA in hot pressing forming.

Figure 5 shows the final length of the specimens. The springback which was approximately 20% was roughly the same throughout the 50°C–130°C temperature range. However, when the temperature exceeded 140°C, the springback became more significant and the highest value of 89% was obtained at 170°C.

The bulge phenomenon appeared on the final shape of specimens when the temperature was below 110°C. Owing to PMMA softening, uniform deformations occurred at temperatures exceeding 110°C.

The higher springback phenomenon that occurred at higher temperatures (i.e. $T > T_g$) indicates that the PMMA exhibits rubber-like behaviour at this stage.

3.2 Creep Test

Figure 6 shows the relationships among relaxation modulus, creep compliance, and time, at 160°C. Before 150 s, the relaxation modulus decreased rapidly. This means that the stress relaxation was very significant and could not be neglected during forming analysis.

3.3 PVT Relationship of PMMA

Figure 7 shows the PVT relationship within the PMMA under pressures of 0.1, 30, 60, and 90 MPa. The glass transition temperature was determined as 110° because there exists a turning point. This point separated two lines of the specific volume with different slopes. The glass transition temperature obtained is very close to that obtained in the compression test.

Overall, the increase of pressure caused a decrease in specific volume at the same temperature. With the same pressure, temperature influenced the specific volume strongly, especially at temperatures that exceeded T_g. However, when the material was cooled from T_g to room temperature, the specific volume approached a constant value.

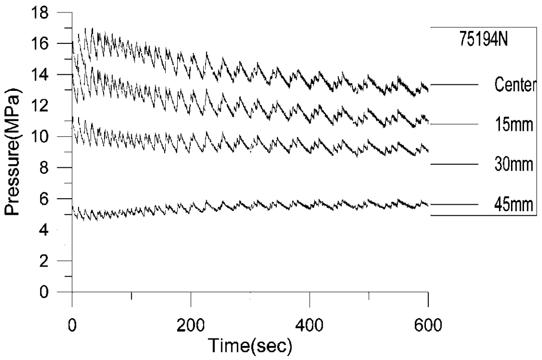

Fig. 8. Pressure variation with time at 75 194 N.

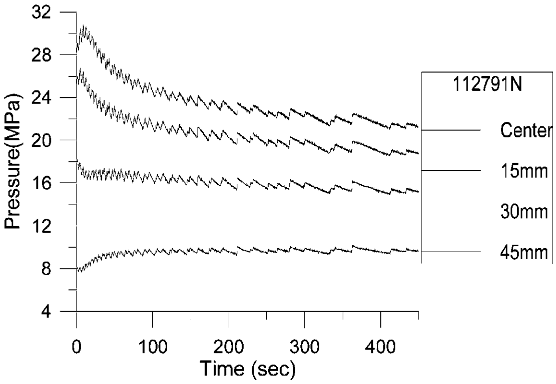

Fig. 9. Pressure variation with time at 112 791 N.

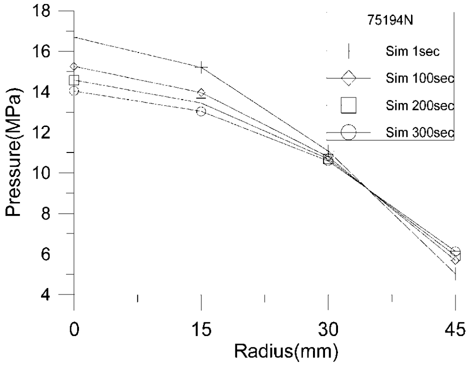

Fig. 10. Simulation result of 75 194 N.

3.4 Pressure Distribution Measurements

Figures 8 and 9 display the pressure measurement results under applied loads of 75194 N (7.9 MPa) and 112 791 N (11.4 MPa), respectively. For each measurement, more than three specimens were tested. However, for brevity, the figures include only the average of these tests. At the positions located at the centre, and 15 mm and 30 mm away from the centre, the pressure increased slightly at the initial stage and then decreased in the final stage. However, at 45 mm from the centre, the pressure decreased initially, and then increased with time. These results reveal that at the centre of the workpiece pressure achieved its maximum value and decreased towards the outer edge. Under both loading conditions, this maximum value was roughly twice the magnitude of the working pressure at initial contact.

The experimental results indicate that the surface pressure decreased with time near the centre of the specimen. Therefore, according to the PVT relationship, its specific volume should increase at the same temperature. In contrast, the specific volume decreased at the outer portion of the specimen. Hence, the centre expansion and the outer contraction deforms the specimen during the cooling procedure.

The surface pressure difference between the centre and the outer portion of the specimen can also be observed from the same figures, that is, the surface pressure difference decreased as time increased, and the larger the applied load, the higher the surface pressure difference. In this way, a smaller working load produced smaller pressure differences, and therefore smaller spe-

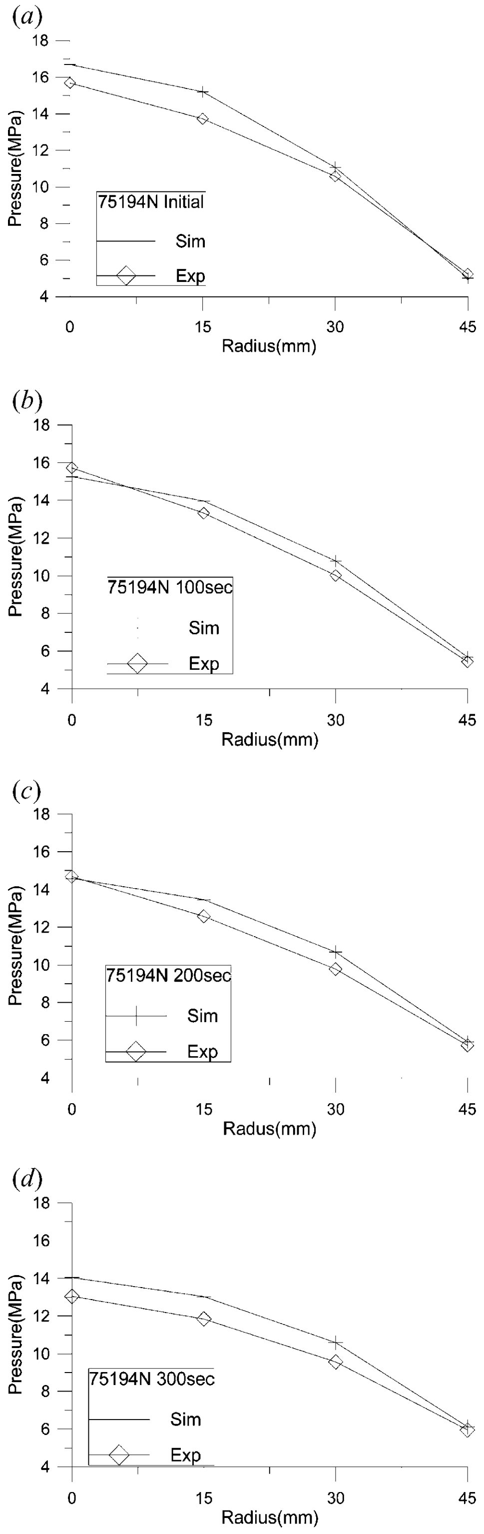

Fig. 11. Simulation vs. measurement at 75 194 N.

cific volume changes. However, if the applied load is not large enough, the shape of the final product will not be assured. Traditionally, the trial-and-error approach is used to determine the preferred load, however, here the FEM approach was used to obtain it.

3.5 Finite-Element Simulation

Figure 10 shows the pressure distribution results under 75 194 N load. Simulation results indicate that the surface pressure characteristics decreased at the centre portion and increased at the outer edge. Figures 11(*a*) to 11(*d*) show the simulation and experimental results under the 75 194 N load. The results indicate that the pressure distribution magnitude predicted by FEM simulation is very close to that of the experiment. The pressure distribution comparisons under the 112 791 N load show similar results.

4. Conclusions

Although polymer materials have been extensively studied, most studies were concerned with the injection moulding process which is characterised by a fast working speed and neglects the time effects. The studies used the rheology properties, for example, the viscosity–shear strain rate relationship from viscometers to simulate the material behaviours of the polymer. This approach is not suitable for the hot pressing process because the time effect is very important in hot pressing.

In this paper, material data from compression tests at various temperatures and creep tests were employed to construct the nonlinear viscoelastic properties of the polymer. With the short-term HYPERELASTIC and the time-dependent VISCOELASTIC commands, the instantaneous displacement and time effect behaviours of PMMA were expressed adequately in the FEM simulation. Subsequently, the possibility of predicting quantitatively the amount of surface pressure distribution during the hot pressing process was investigated. The good agreements between simulation and experimental results reveal that the FEM approach can be an effective tool in simulating the hot pressing process.

Acknowledgements

The authors would like to thank the Department of Mechanical Engineering of the National Taiwan University and the CAE Laboratory of the National Tsing Hua University for offering their experimental instruments. We also thank the Mechanical Industry Research Laboratory of the Industrial Technology Research Institute for the use of the hot pressing machine. Finally, we thank the National Center for High-Performance Computing for offering their computing facilities.

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