Int J Adv Manuf Technol (2016) 82:859–866
DOI 10.1007/s00170-015-7394-6

ORIGINAL ARTICLE

Experimental study on elastic deformation molding process for generating aspheric surface glass

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Received: 21 July 2014 / Accepted: 5 June 2015 / Published online: 27 June 2015

Abstract The elastic deformation machining method has been demonstrated to be a novel optical manufacturing approach which can greatly reduce and simplify the production of large aspheric lens. Upon completion of the machining process, the workpiece under process will be shaped into a desired surface form of mold. The method allows the lapping and polishing of aspheric optical surfaces using a large lapping or polishing tools. The subject of this study is to determine the surface shape of the finished glass workpiece after the lapping process of the elastic deformation machining process associated with molding. The experimental and finite element analysis (FEA) results were compared with the shape of the molded surface form. The form accuracy between the optical glass and mold is within 1.6 μm (within radius 32 mm). The conclusions show that the method proposed is effective for machining the aspheric optical glass with proper elastic deformation machining parameters.

Keywords Elastic deformation · Aspheric surface · Glass lapping · Glass molding · Finite element analysis

1 Introduction

The aspheric lenses have been widely used in optical, opto-electrical, and opto-mechanical systems. The aspheric lens fabrication requires a series of complex machining, time-consuming manufacturing processes. Traditional methods to produce aspheric lenses are material removal processes, such as turning, milling, grinding, and polishing technologies [10, 4]. These manufacturing techniques can be used to fabricate optical lenses with very smooth surfaces. However, they have expensive manufacturing cost and are unpractical for mass production of aspheric lenses needed in household products.

The glass molding has greatly advanced the fabrication technologies as a promising way to mass produce aspheric glass lenses [3, 5, 8]. In the method, a glass lens is produced by compressing glass melting at a high temperature and replicating the shapes of the mold to the lens surface without need for further machining process. The method has advanced higher production efficiency than the conventional cold working methods. However, because of heat transfer phenomenon and high temperature at deformable area, the mechanical characteristics of glass can be changed in this molding process [11], as a result, the shape accuracy of the molded lens changes significantly and optical properties of the lens remain with residual stress distribution within the lens [6].

In this background, the elastic deformation machining method has been demonstrated to be a novel optical manufacturing approach which can greatly reduce and simplify the production of large aspheric lens. This method elastically deforms the workpiece prior to the lapping process, and the amount of deformation is limited by loading. While the workpiece has deformed shape, the bottom side of the workpiece is lapped to a flat surface. When the load is released, the bottom surface of the workpiece will be shaped into an aspheric shape [7, 9, 12], while the top surface will restore to its flat

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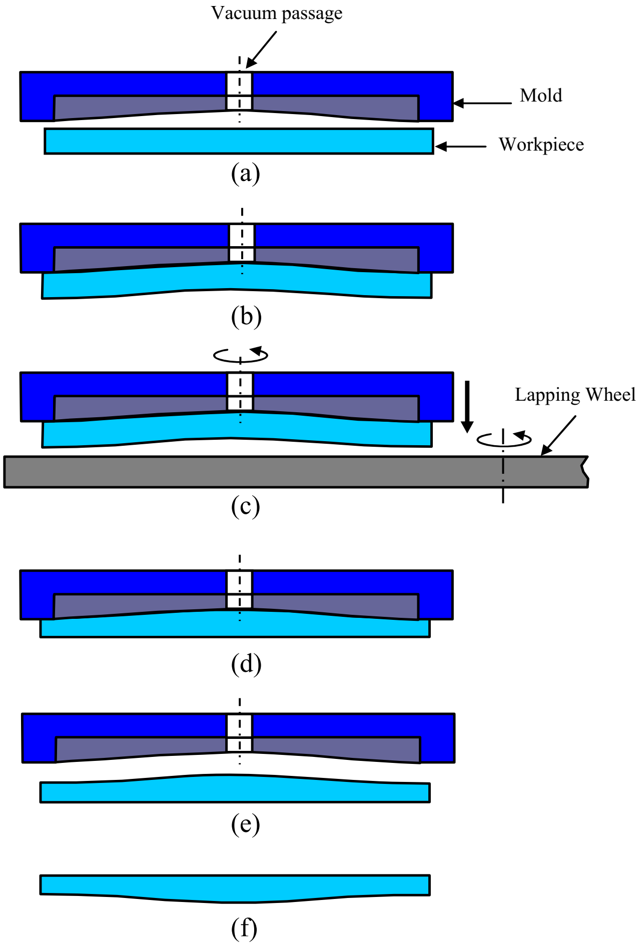


Fig. 1 (*a–f*) Schematic illustration of a lens elastic deformation process with the mold

surface form. The thickness of the workpiece is reduced in the lapping process while the load remains unchanged. It caused the deflection of the workpiece to be greater than the desired surface form when the bottom surface of the workpiece is lapping to flatness. Therefore, in order to produce form accuracy independent with change of workpiece thickness in this method, the study will employ a mold with its surface close to the desired surface form of the lens. The top surface of the plate will deform and be in contact with the molded surface once vacuum is applied. After the lapping and polishing processes, and with the load removed, the top surface will restore to its flat surface form under the material's elasticity, thus making the bottom surface the shape of the molded surface form.

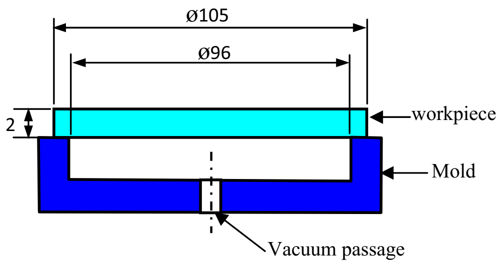


Fig. 2 Experiment model of vacuum pressure with deformation curve of the workpiece

The results for deflection and measurement of form accuracy are shown in this study. The form accuracy and deflection were investigated with MarForm MMQ 400 measurement instruments. The conclusions show that the method proposed is effective for machining the aspheric optical glass with proper elastic deformation machining parameters.

2 Elastic deformation machining method model with an aspheric surface molding

The process of the elastic deformation machining method is shown in Fig. 1. The virgin workpiece is usually a round flat with two surfaces polished to certain flatness as shown in Fig. 1(a). When vacuum is applied to the back of the workpiece through the center hole in the mold, the workpiece is pulled upward in the middle. The edge of the workpiece is supported by the mold and therefore will not move. The result is a deformed aspheric shape as shown in Fig. 1(b). While the vacuum keeps the workpiece at its deformed state and completely in contact with the mold, the workpiece and the holder start to rotate and are brought downward into contact with the lapping wheel. The side of the workpiece that is in contact with the lapping wheel is lapped and polished to optical flatness (as shown in Fig. 1(c, d)). When the vacuum is turned off and the workpiece is released from the mold (as shown in Fig. 1(e)), the bottom surface of the workpiece will be shaped into the aspheric shape (as shown in Fig. 1(f)) as the top surface returns to its original flat surface form due to material elasticity.

Table 1 Material properties of B270 optical glass

Density (kg/m^3)	Young's modulus (GPa)	Knoop hardness HK100 (kg/mm^2)	Poisson ratio
2550	71.5	542	0.208

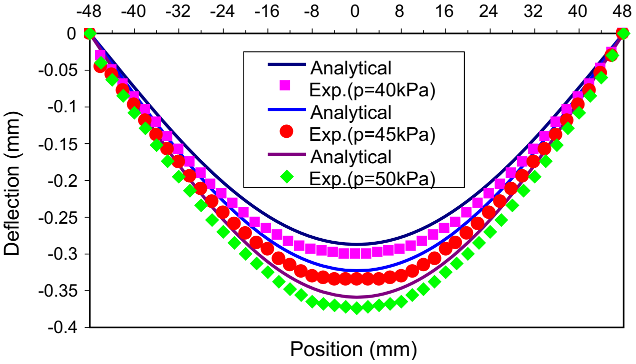


Fig. 3 Relationship between the vacuum pressure and the deformation curve

3 Relation between vacuum pressure and the deformation curve of workpiece

3.1 Analytical model

The surface form of the workpiece is calculated by applying the elastic theory. The workpiece, which is fixed on the holding device, is deformed by the vacuum pressure, while its circular edge is supported by the holding device; the deflection ω is given by

$$\omega = \frac{p(a^2-r^2)}{64D}\left[\frac{5+v}{1+v}a^2-r^2\right] \qquad (1)$$

where r, a, and p are the radial coordinate, plate radius, and load, respectively, and the constant $D=Eh^3/12(1-v^2)$ is known as the flexural rigidity of the plate, with Young's modulus E, Poisson's ratio v, and thickness h.

The maximum deflection occurs at the center of plate and is given by

$$\omega_0 = \frac{pa^4}{64D}\left(\frac{5+v}{1+v}\right) \qquad (2)$$

3.2 Experiment model

The elastic deformation of the workpiece is dependent on the pressure distribution caused by vacuum pressure. Therefore, the profile accuracy resulted will be highly dependent on the pressure as well. The relation between the vacuum pressure in the holder and the deformation curve of the workpiece is carried out. In this experiment, the edge of glass workpiece is supported by the holding device, and the vacuum pressure is set at p=40, 45, and 50 kPa, while the thickness and diameter of the workpiece are h=2 mm and D=105 mm, respectively. The glass workpiece properties are listed in Table 1. The experiment model is shown in Fig. 2.

The influence of the vacuum pressure in the holder to deformation curved of workpiece is presented in Fig. 3. The deviation between theoretical calculations and the experimental results is shown in Fig. 4.

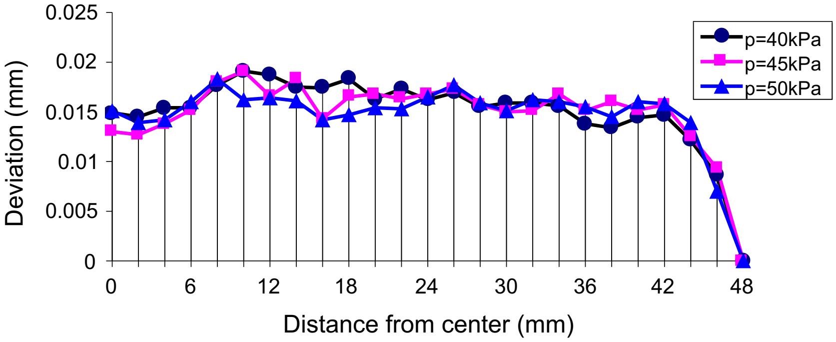


Fig. 4 The form deviation profile between experiment and theoretical results

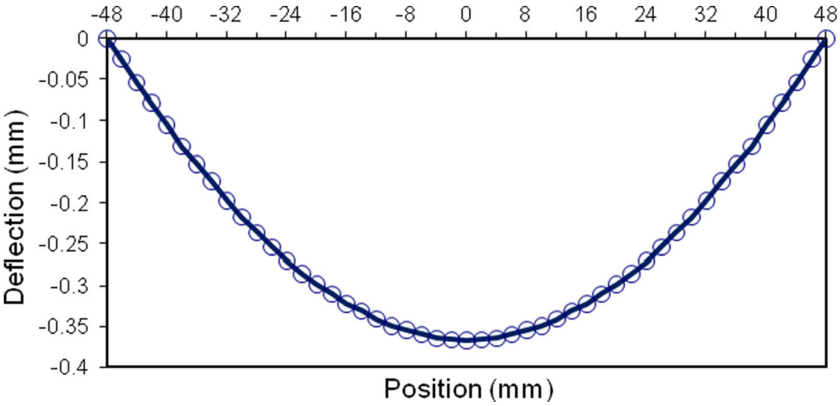


Fig. 5 The profile of the mold

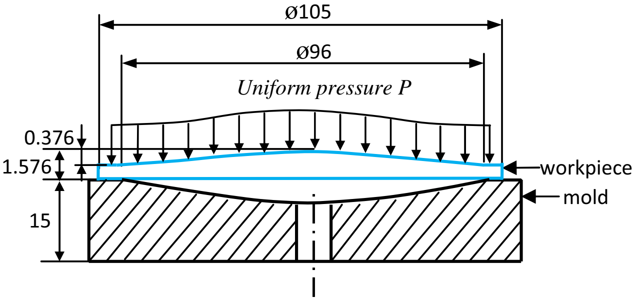


Fig. 6 FEM model

Based on the experimental results, the maximum deflection of mold profile is selected about 0.37 mm that the glass workpiece which is deformed and pulled upward to touch with the mold is not broken.

4 Finite element method simulations

In the simulation process, the profile of the mold has a maximum deflection at the center about 0.376 mm. The profile of the mold is shown in Fig. 5.

Computer simulations of glass contact with molding process were carried out using a commercially available finite element method (FEM) program Abaqus 6.10/Explicit. The program is capable of simulating large deformation of glass under applied pressure conditions of close contact with the mold. It is necessary to determine the value of applied vacuum pressure in machining process. The FEM model is shown in Fig. 6

In this model, the mold is assumed as a completely rigid body; the glass workpiece preform which upper surface is set to be the profile of mold is deformable. The workpiece is deformed and lapped to be flat surface in the machining process, so the thickness of the workpiece will be decreased. In this case, the applied pressure is smaller than that in the case which the workpiece is only deformed.

To start simulation, the FEM model was built as axisymmetric. The mold chosen is an analytical rigid shell and the workpiece is a deformable shell. The analytical step of the model is "dynamic, explicit". The interaction and contact property is "surface-to-surface contact" and "penalty contact method" respectively. The mesh of the workpiece and boundary conditions are shown in Fig. 7.

The value of uniform pressure is selected as 55, 60, 65, 70, 75, and 80 kPa. Based on the finite element analysis results (as shown in Fig. 8), the center of the workpiece is deformed and will first contact with the mold, and then the radius of contact area will expand from the center to edge when the applied pressure is increasing.

The deformation of the workpiece under different applied pressures and the profile of the mold are shown in Fig. 9.

The deviation results between the workpiece and mold under different applied pressures is presented in Fig. 10.

Based on the deviation results, the deviation between the workpiece and mold will be decreased as the applied pressure is increased. But when the applied pressure reaches over 70 kPa, the deviation does not seem to decrease. The minimum deviation is about 17 μm when the applied pressure is

Fig. 7 FEM simulation model

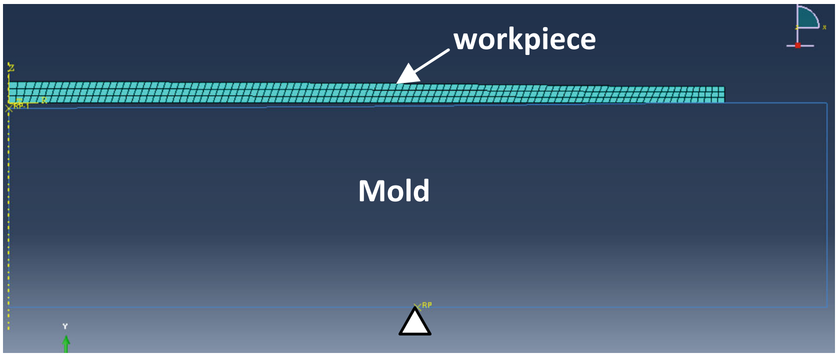


Fig. 8 FEA result (at P=70 kPa)

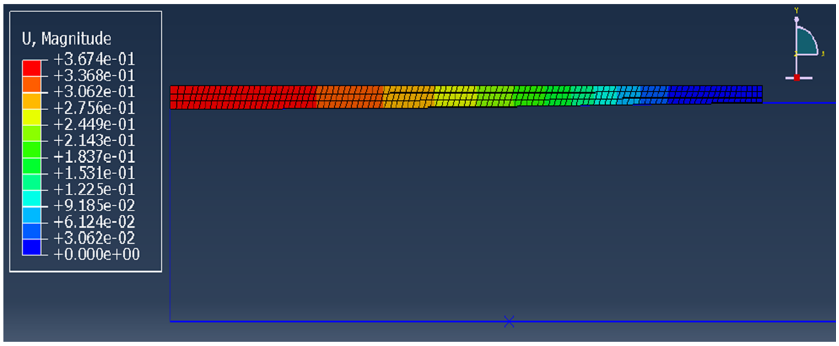
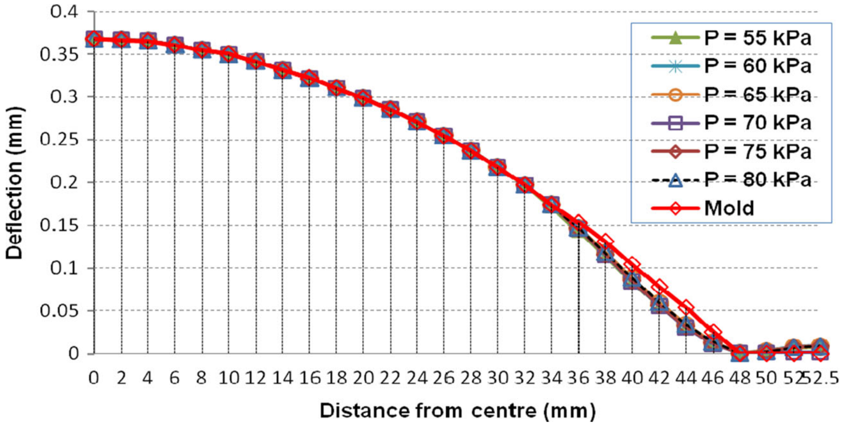


Fig. 9 Comparison of FEA results and mold surface



70 kPa, so that the vacuum pressure inside the mold will be selected at 70 kPa during machining process.

5 Experimental study

The experiment was carried out on a Nanopoli-100 precision polishing machine. The mold surface used in this process is shown in Fig. 11.

The mold is machined on a CNC machine and the form error of the mold is within P-V 3 μm. The curve surface of the mold is measured by the MarForm measurement instrument. The form of curve surface is shown in Fig. 12.

Base on the finite element analysis (FEA) results, the vacuum pressure inside the mold is set to be 70 kPa. This vacuum pressure value is enough so the workpiece and mold can touch closely in the machining process. The machining progress is performed by lapping and polishing later. The lapping is through the relative motion between the granule and the workpiece, affected by slurry through contact under lapping load [2]. The contact zone between the workpiece and the tool is fed continuously with silicon carbide (SiC) and cerium oxide

Fig. 10 Deviation between the workpiece and mold

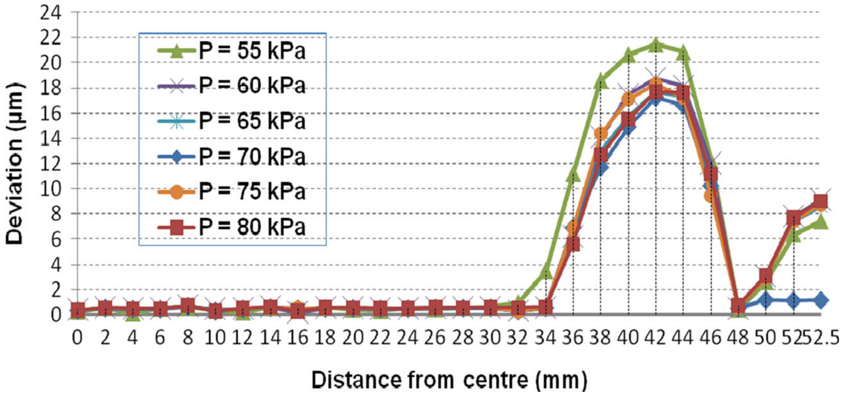


Fig. 11 The mold surface in elastic deformation machining

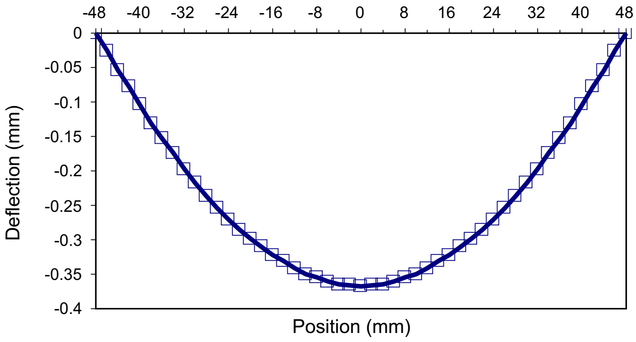


Fig. 12 The profile of the mold (measured by MarForm)

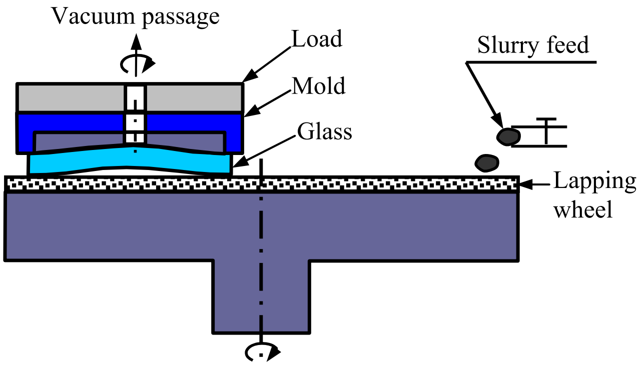


Fig. 13 Principle of loose abrasive lapping

(CeO_2) abrasive grain slurry (see Fig. 13). In the lapping process, a rigid iron surface covered by a cloth layer is moving under load over a glass surface, with abrasive particles suspended in water between them. All of the machining parameters remain unchanged as that in the lapping process, except that the abrasive is changed from SiC to CeO_2 in the fine polishing process [1]. The parameters for the machining process are listed in Table 2.

In addition, the vacuum pressure in the mold is modified by a flow control valve. It is used to keep the vacuum state in the mold stable when the glass plate is lapped. The medium vacuum pressure is set at 70 kPa in this experiment and displayed by vacuum pressure switch. The machining experiment process is shown in Fig. 14.

6 Results and discussion

In this experiment, the glass plate is elastically deformed to an aspheric surface form which closely contacts by vacuum pressure. The bottom side of the plate is then lapped to a flat surface form while keeping the plate in a deformed state. Figure 15 shows the deflection results of a plate after the lapping process and recovering from elastic deformation after released from vacuum and FEA results with applied pressure at 70 kPa. In this experimental result, the maximum deflection at the plate center is 0.3674 mm while the maximum deflection at the center of the mold is 0.3676 mm. The maximum deviation between the center of the mold and the experimental results is within 0.2 μm. In addition, the maximum deflection in the FEA results is 0.3672 mm. The maximum deviation between the center of the mold and the FEA results is within 0.4 μm.

Table 2 Lapping and polishing conditions

Items	Lapping	Polishing
Abrasive	#1000 SiC	#10000 CeO_2
Abrasive concentration in slurry (wt%)	10	10
Machining load (N)	20	15
Rotating speed of lapping plate (rpm)	60	30
Machining time (min)	240	80

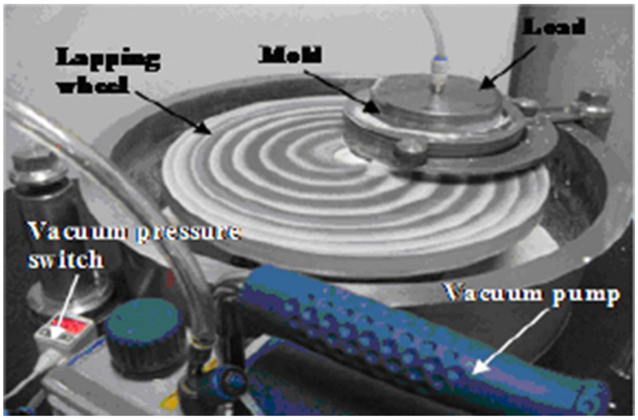


Fig. 14 Experimental setup in the lapping processes

According to experimental and FEA results, the deviation between the experimental and FEA results and the mold profile are calculated (as shown in Fig. 16).

Based on the deviation results, the form accuracy is less than *P-V* 1.6 μm within the radius about 32 mm, but if the radius exceeds 32 mm, the form accuracy increases rapidly.

The reason for increasing form error can explain as follows:

- The profile of the mold is designed above has not been optimized. It means that the workpiece and mold do not touch completely in the machining process. The experiment and FEA results showed that the workpiece and mold touch closely within the radius of 32 mm. When the radius exceeds 32 mm, the workpiece and mold do not seem to touch closely. This is the reason for increasing form error of workpiece in deformation machining process.
- In the machining process, the workpiece is deformed and pulled upward to touch closely with the mold. The form error of the workpiece is also generated in this process (as shown in Fig. 17). The edge of the workpiece is supported by the mold and placed on a lapping plate. In addition, the machining load also affects on edge of the workpiece. Thus, the bending moment is generated in the edge of the workpiece (as shown in Fig. 18). This is the cause of the difference between experiment and FEA results. So the form error between experiment results and mold profile is larger than that between FEA results and mold profile.

The glass plate after final machining is shown in Fig. 19.

Fig. 15 Comparison of experimental and FEA results with mold profile

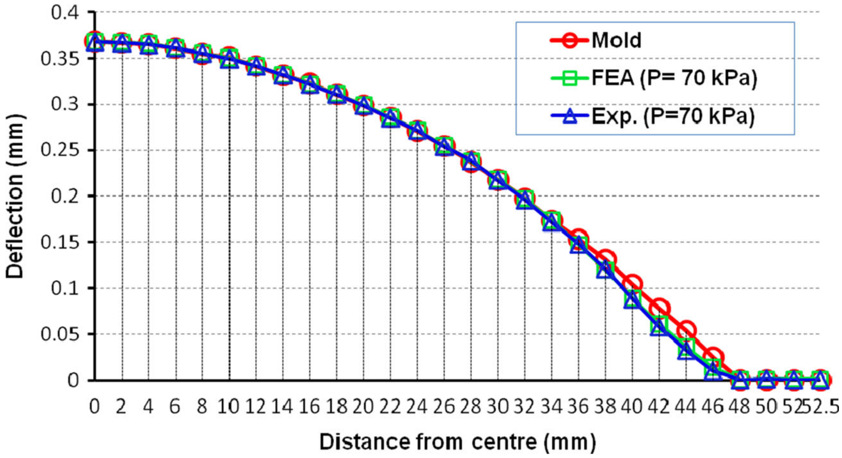
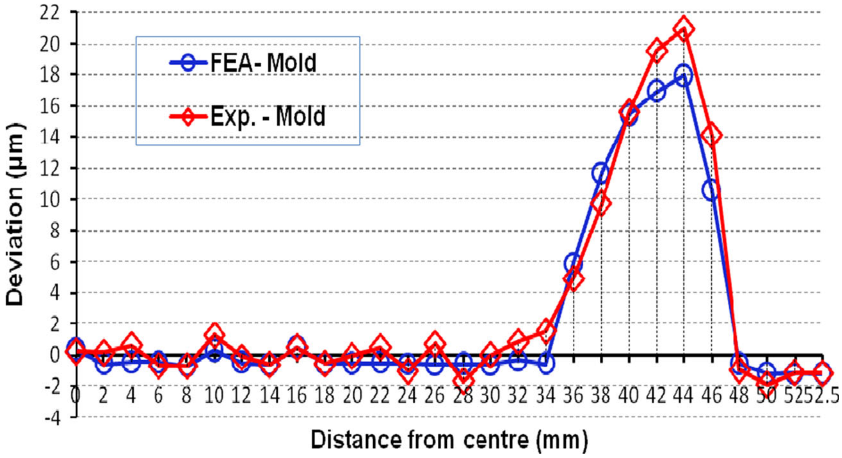


Fig. 16 The form deviation profile between experiment and FEA with mold results



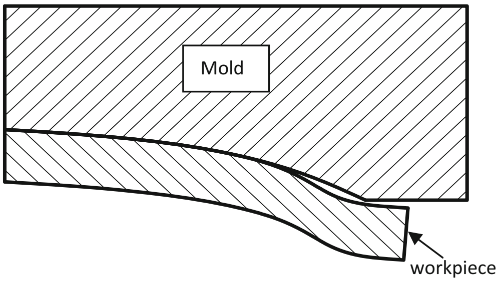


Fig. 17 Form error of workpiece when it touch with the mold

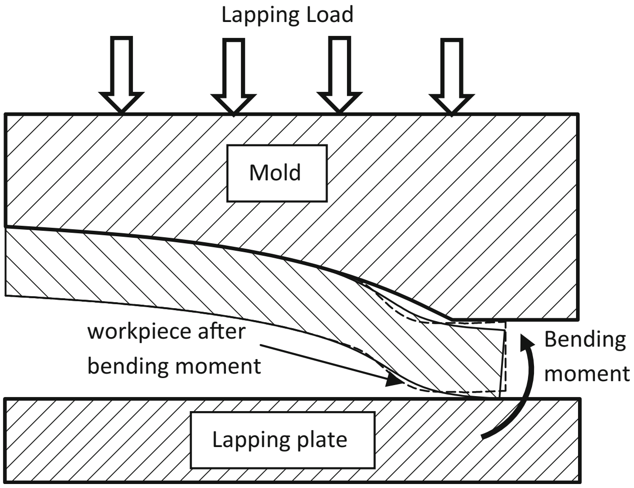


Fig. 18 Form error of workpiece in machining process

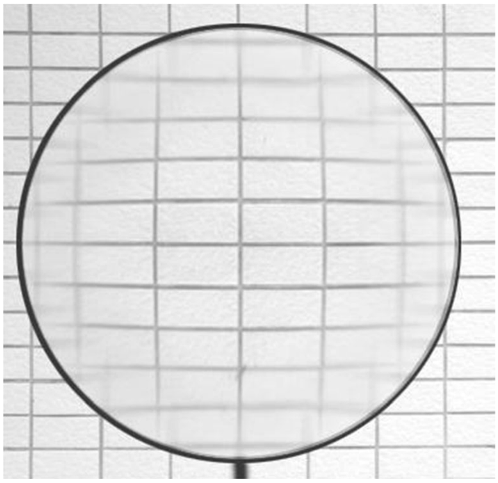


Fig. 19 Fabricated glass plate

7 Conclusions

This paper outlined a method that exploits elastic deformation properties of a plate and utilizes plane lapping process associated with molding to fabricate aspheric surfaces. From the experiment results, we can conclude the following:

1. In the lapping process, the thickness of the workpiece is reduced while the vacuum pressure remains unchanged. The thickness difference does not affect the form accuracy of the workpiece significantly in the elastic deformation machining method associated with molding because the deflection of the workpiece is controlled by the form surface of the mold.
2 The form accuracy produced is dependent on the form accuracy of molding. In this experiment, the workpiece is deformed to closely contact with molding surface. This state is maintained through the machining process. The form accuracy of the workpiece is less than *P-V* 1.6 μm within the radius 32 mm. The form accuracy will be increased when the radius exceeds 32 mm. This accuracy can be improved if the profile of the mold is optimally designed to the workpiece and the mold completely touches. Besides that, the bending moment affects the deformation of workpiece and needs to be controlled and reduced to a minimum. This problem should be studied in the future work.
3. The elastic deformation machining process described in this paper outlined an advanced fabrication method in which the workpiece is deformed by vacuum pressure to completely contact with molding surface. It is suitable for machining complex surfaces with thin glass thickness and low complexity.

Acknowledgments This project is supported by the National Science Foundation of China (grant no. 50975085) and the Natural Science Foundation of Zhejiang Province (Y1101095).

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