Finite Element Analysis of PGM Process for Wafer Based Lens Array

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Abstract: In order to study the PGM process for wafer based lens array, we established a 3D finite element model of glass wafer with lens array by using the submodel technique in ABAQUS. Then assessment criteria of the molded lens and influence of different PGM process parameters were investigated thoroughly. The obtained results show that during the molding stage, proper molding pressure can help the lens fill better and decrease the sag height deviation significantly. While during the annealing stage, holding pressure is essential for keeping the molded lens' structure and position, but residual stress must be considered at the same time.

1. Introduction
In the last twenty years, precision glass molding (PGM) technique has been developed rapidly and studied widely for its advantages of high volume, low cost, environmental friendliness and nearly net-shape [1]. This technique can be used to manufacture spherical and aspherical lenses, as well as various complicated optical elements such as micro lens array, fresnel lens, freeform optics, wafer level optics, etc. [2-3]. However, due to the temperature and pressure influence during the PGM process, some defects could be introduced, like profile deviation, residual stress and pitch error, which would affect the performance of molded optics [4-6].

In this paper, a 3D finite element analysis of PGM process for the whole glass wafer as well as partial single lens submodels is conducted, and three essential PGM process parameters, namely molding pressure in molding stage, holding pressure and cooling speed in annealing stage, are simulated. Based on the results, effects of the process parameters on selected evaluation criteria, such as residual stress of glass wafer, sag height deviation of molded lens and pitch error of lens array, are studied thoroughly.

2. Finite element model of wafer based lens array
The structure of molded glass wafer based lens array is shown in figure 1. Its diameter is 50mm, and thickness is 5mm. A 5x5 lens array is located in the center, and pitch of the lens is 6mm. Dimensions of a single lens is illustrated in figure 1(c).
Considering the large difference in size between glass wafer and the tiny lens array, a 3D finite element mesh model is employed with submodeling technique in ABAQUS software. The submodeling technique is an effective method to study a local part of a model with a refined mesh based on interpolation of the solution from an initial relatively coarse global model. First, the complete coarse model is analyzed to confirm the maximum response area. Then a refined mesh model on specific cared part is used to get more detailed information with results from the complete model as boundary conditions.

In our study, 1/8 of the whole model is adopted by using the plane symmetry for simplification, and its global coarse mesh model is shown in figure 2(a). Local refined mesh of central submodel, which highlighted in the elliptical area of figure 2(a), is illustrated in figure 2(b). Since large deformation of glass wafer occurs during the molding stage, mesh size of wafer should be much smaller than the molds to acquire more precise molded lens shape.

In this study, molding, annealing, fast cooling and nature cooling stage of the PGM process are simulated in ABAQUS with a uniform temperature distribution of glass wafer and molds as initial condition. Temperature of molds and molding pressure in simulation are presented in figure 3. The material of glass wafer is G-11 and molds are WC. Generalized Maxwell model [7] and Tool-Narayanaswamy-Moynihan (TNM) model [8] are proposed to represent the stress relaxation and structural relaxation properties of glass wafer.
3. Analysis of simulation results

3.1. Distribution of residual stress

The residual stress distribution of 3D global model is shown in figure 4. It decreases from center to outer along the radius of wafer, and some larger stress locates at the edge of each single lens. Residual stress distribution of 6 lens submodel are illustrated separately in figure 5. From figure 5(a) we can find that in the central lens, the maximum residual stress locates at the center of submodel. Meanwhile, comparing with the global model, residual stress is improved at the edge of spherical shape as a result of the refined mesh. For the other lens submodels, as they are further from the center, shrinkage of wafer along radius direction is larger than the inner shrinkage of single lens, and glass wafer is still contacted with the upper mold during annealing stage, so large residual stress generates at the inner side of spherical shape edge.

Figure 3. (a) Temperature of molds and (b) molding pressure curve in simulation

Figure 4. Contour plot of residual stress in glass wafer for global model
3.2. Deviation of sag height for each lens
Deviation of sag height is utilized as a simplified evaluation criteria of molded lens curve deviation, and the results of each submodel are represented in figure 6. Sag height deviation of lens 1, 2 and 3 increases as they are located along the radius direction of wafer from center to edge. Similar results can be found among lens 1, 4 and 6. So the results declares that the further each submodel lens is from center, the larger of its sag height deviation.

![Figure 6. Sag height deviation of each lens submodel](image)

3.3. Pitch error for lens array
Simulated central position of each lens submodel is listed in table 1. Lens 1’s center is regarded as origin point. Lens 2 and 3 are located at axis X with a zeros y position, and lens 4 and 6 are located along the 45° of axis X and Y with an equal x and y position. Pitch error in the table is calculated by the designed size minus simulated central position of adjacent lens.

![Table 1. Pitch error for lens array](image)
Table 1. Pitch error of lens arrays

| NO. of lens submodel | Designed position of lens center [x, y] (mm) | Simulated position of lens center [x, y] (mm) | Pitch error along axis X-Px (μm) | Pitch error along axis Y-Py (μm) |
|----------------------|---------------------------------------------|---------------------------------------------|---------------------------------|---------------------------------|
| 1                    | 0, 0                                       | 0, 0                                       | -                               | -                               |
| 2                    | 6, 0                                       | 5.975, 0                                   | 25                              | -                               |
| 3                    | 12, 0                                      | 11.941, 0                                  | 34                              | -                               |
| 4                    | 6, 6                                       | 5.969, 5.969                               | 31                              | 31                              |
| 5                    | 12, 6                                      | 11.932, 5.968                              | 37                              | 32                              |
| 6                    | 12, 12                                     | 11.927, 11.927                             | 42                              | 41                              |

From table 1 it can be concluded that central position of each molded lens is smaller than the designed position. In addition, the further each lens submodel is from center, the larger of its pitch error. The reason is that thermal expansion coefficient of the glass wafer is much larger than mold material. So shrinkage of molded lens in wafer during the cooling stages is also much bigger, and is positive correlated with its central position from the wafer center.

4. Investigation of PGM process parameters

From the above simulation results we can infer that residual stress of lens 1 is the largest, while sag height deviation and pitch error of lens 6 are the largest. Nevertheless, it's a little complicated to compute the pitch error, so the designed position x of lens 6 minus the simulated result, expressed as $P_{x6} = 12 - x_6$, is used as a simplified criteria replacement. Therefore, in the following investigation of PGM process parameters, sag height error and $P_{x6}$ of lens 6 as well as residual stress of lens 1, are treated as the optimization objectives.

4.1. Molding pressure during molding stage

Molding pressure is the forming force on glass wafer by upper mold during molding stage, which is a principle parameter in the PGM process. If molding pressure is insufficient, structure of molded lens can't be formed properly, leading to a large shape deviation. On the contrary, if molding pressure is too large, transient stress in glass wafer might be too high to make it cracked. In this subsection, 5 different molding pressures are selected to simulate the molding stage, other parameters are kept the same as section 2.

Figure 7 shows the molded curve of lens 6 under different molding pressure. As the molding pressure increases, the molded curve is more closed to the designed size. Details of sag height deviation are list in table 2. When the molding pressure increases to 16MPa, sag height deviation is reduced to a reasonable level. Nevertheless, when keeping increasing the molding pressure, the deviation can't be reduced any more. So it can be inferred that when the molding pressure is below 16MPa, lens 6 is not well filled in the mold, which introduces a higher sag height deviation. When the molding pressure reaches 16MPa and even more, lens 6 is well filled, and the final deviation mainly comes from the shrinkage of later cooling stages.

![Figure 7. Molded shape of lens 6 at different molding pressure](image-url)
Table 2. Simulation results of different molding pressure

| Molding pressure (MPa) | Sag height deviation of lens 6 (μm) | Pitch error along axis X of lens 6 (μm) | Maximum residual stress of lens 1 (MPa) |
|------------------------|--------------------------------------|-----------------------------------------|----------------------------------------|
| 4                      | 79.6                                 | 78                                      | 5.4                                    |
| 8                      | 48.2                                 | 73                                      | 8.5                                    |
| 12                     | 17.5                                 | 66                                      | 10.3                                   |
| 16                     | 4.7                                  | 58                                      | 11.6                                   |
| 20                     | 4.7                                  | 58                                      | 12.7                                   |

Much the same as sag height deviation, pitch error along axis X of lens 6 decreases as the molding pressure increases, and the pitch error keeps the same with molding pressure at 16MPa and more. On the other hand, with the molding pressure increases, maximum residual stress of lens 1 keeps raising.

Based on the above analysis, for the investigated glass wafer model, molding pressure of 16MPa is appropriate to ensure the lens submodels be filled well and keep a reasonable residual stress.

4.2. Holding pressure and cooling rate during annealing stage

During the annealing stage, upper mold is still contact with the glass wafer with a minor holding pressure to make the wafer fill better. In the meantime, temperature of the wafer and molds cools down slowly from the molding temperature 585°C to lower than the glass transition temperature. In this study, temperature at the end of annealing stage is set at 460°C. 2 different holding pressures and 3 different cooling rates are selected to simulate the annealing stage and investigates their coupled effect on molded lens. Detailed results are clarified in table 3.

Table 3. Simulation results of different holding pressure and cooling rate

| Holding pressure (MPa) | Cooling rate (°C/s) | Sag height deviation of lens 6 (μm) | Pitch error along axis X of lens 6 (μm) | Maximum residual stress of lens 1 (MPa) |
|------------------------|---------------------|--------------------------------------|-----------------------------------------|----------------------------------------|
| 0                      | 0.5                 | 20.5                                 | 86                                      | 4.3                                    |
| 0                      | 1                   | 18.4                                 | 81                                      | 5.6                                    |
| 0                      | 2                   | 15.6                                 | 77                                      | 7.5                                    |
| 0.4                    | 0.5                 | 2.9                                  | 43                                      | 12.9                                   |
| 0.4                    | 1                   | 4.7                                  | 58                                      | 11.6                                   |
| 0.4                    | 2                   | 7.3                                  | 65                                      | 9.8                                    |

From table 3, it is clearly showed that sag height deviation of lens 6 with 0.4MPa holding pressure is much smaller than that without a holding pressure. In the 3 simulations with 0.4MPa holding pressure, larger cooling rate leads to shorter annealing time, thus the operation time of holding pressure on wafer is shorter and the sag height deviation becomes larger. On the contrary, in the 3 simulations without holding pressure, glass wafer shrinks without constraint during the annealing stage. According to the structural relaxation properties of glass material, when the cooling rate is smaller, equivalent expansion coefficient is larger [9], hence the volume of glass varies larger and the sag height deviation increases. Similar results are also found for pitch error along axis X of lens 6.

When observing the maximum residual stress of lens 1, simulations with 0.4MPa holding pressure are larger than that without it, indicating that the holding pressure will increase the residual stress. Moreover, with the cooling rate reduces, time of annealing stage becomes longer and so is the operation time of holding pressure, thus the residual stress increases. In addition, the 3 simulations without holding pressure represents the effect of cooling rate alone. Maximum residual stress raises with the cooling rate increasing.

5. Conclusion

In this study, a 3D finite element analysis of wafer based lens array was proposed and several parameters during the PGM process were discussed in detail. Main conclusions of this research are summarized as follows:
(1) With closer to the center of lens submodel, the residual stress increases, while the sag height deviation and pitch error reduces.

(2) During the molding stage, a proper molding pressure can ensure the lens submodel fill well and decrease sag height deviation and pitch error obviously. But when increasing the molding pressure further, sag height deviation and pitch error keeps the same, while residual stress enlarges.

(3) During the annealing stage, holding pressure is necessary for the molded shape and position of lens submodels, but will enlarge the residual stress. Meanwhile, reducing cooling rate can decrease the residual stress, but also increases the annealing time, which introduces a larger influence by holding pressure conversely.

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