The Simulation and Experimental Analysis of the Gradient Temperature Forming of the Bifocal Mirror Based on Spin-casting

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Abstract. This research employed the methods of simulation analysis and experiment to study the movement trend of the glass melt and the deviation of the junction position of the surfaces in the spin-casting process of the bifocal mirror. By comparing the measurement result of the surface shape in the experiment with the predicted result of that in the simulation, the deviation between these two results is 6.5 μm. It is proved that the simulation can predict the surface shape of the mirror blank obtained by spin-casting of the bifocal mirror. Through the results of simulation and experiment, it is found that there is a significant deviation between the junction position of the reflecting surfaces and the expected one. Therefore, by changing the position of the insulation wall, the purpose of compensation for the junction position of the surfaces can be achieved. When the insulation wall was set at different positions for many times of iterative simulation calculation, the deviation of the junction position of the surfaces was reduced from 4.358mm to 3.76 μm.

Keywords: Mirror blank; Spin-casting; Simulation; Bifocal mirror.

1. Introduction
With the deepening of human exploration of the universe, astronomical telescope as the primary tool of astronomical observation has been widely used [1,2,3]. The bifocal mirror is the main components of some modern optical systems [4]. Compared with ordinary aspheric mirror, bifocal mirror possesses coaxial aspheric surfaces with different profiles in a different area, so that one mirror could have two coaxial focuses at the same time [5,6]. The required length of the optical system then can be shortened, so as to improve the stiffness of the large aperture reflective optical system and simplify the three-mirror-anastigmat system [7].

As a mirror with multiple aspheric surfaces, the processing and forming of a bifocal mirror is always a difficult problem [8,9]. The size of the mirror blank processed by traditional aspherical mirror processing methods will be limited. Meanwhile, the processing time will also be extended, much material waste will be caused, and the wastewater and slag produced by the processing will bring heavy environmental pollution.

In the process of mirror blank forming, the usage of gradient temperature forming method based on spin-casting avoids the grinding process of the inner reflecting surface. This forming method takes advantage of the centrifugal force and the unique characteristics of glass, which is that the viscosity of glass is different at different temperatures and glass melts with different states of viscosity can coexist.
To control the temperature gradient, a heat insulation wall is added to the mould, which was used to form the traditional single curved surface. A coaxial bifocal mirror can be formed by melting the glass material and changing the rotating speed of the mould in different forming areas, and after that, only polishing of the mirror blank is needed. The formed mirror has a high surface quality and a certain surface shape accuracy. The whole forming cycle is short, and the processing cost is low, which provides an effective forming method for the sophisticated bifocal curved mirror.

For this gradient temperature forming method based on spin-casting, numerical simulation was carried out in this research, and the data of simulation and experiment were compared employing analogy experiment. The deviation between the simulation result and the experimental result is in micron grade, which meets the requirements of mirror blank processing. Therefore, the simulation calculation method can be used to predict the shape of the curved surface and the injunction position of the inner and outer reflecting surfaces after forming. Due to the deviation between the surface range formed in spin-casting and the expected surface shape, the simulation calculation was adopted to analyse the change of the junction position of the curved surfaces. Then, by changing the position of the heat insulation wall, the position deviation at the junction point of the two curved surfaces was compensated, so that the deviation can be significantly reduced. It verifies the feasibility of the way of changing the position of the insulation wall through the simulation calculation.

2. Experimental Settings and Process

The experimental process is shown in Figure 1. In the experiment, a mould with an internal diameter of 100mm and a height of 50mm was selected, and an insulation material with an internal diameter of 50mm and a height of 15mm was put inside of the mould as the heat insulation wall. The height of the epoxy resin pool in the mould is 15mm. The specific experimental materials are shown in Table 1. The forming process of the bifocal mirror is as follows:

- Homogeneously heating: spray high-temperature mould release agent inside the mould, put the ingredient of glass into the mould, and heat the mould evenly until the required processing temperature is reached.
- The first step of spin-casting: Rotate the mould according to the pre-set rotation speed, keep the rotation speed unchanged until the glass melt inside the mould reaches a stable state.
- The first annealing: keep the mould rotation speed unchanged, cool the glass at a constant rate until the temperature drops below the temperature of $T_g$, and keep the temperature unchanged.
- Thermal radiation: use thermal radiation to heat the inner of formed glass. Due to the existence of the heat insulation wall, a temperature gradient will be formed inside the glass, and there will be different flow states in the inner and outer of the glass. The inner part is in the same flow state as it is in the first step of spin-casting, and the outer part is in the non-flow state below the temperature of $T_g$.
- The second step of spin-casting: change the rotation speed of the mould, so that the inner part of the glass forms the second curved surface until the liquid level reaches stability.
- The second annealing: cool the glass at a constant rate until it reaches the temperature below the temperature of $T_g$.
- Demoulding: take out the mould from the heating furnace, wait for the glass to cool to room temperature and take it out.
- Remove the material flow from the inner part to the outer part in the second step of spin-casting.

Table 1. The material parameters of H-K9L optical mirror.

| Material properties          | Value         |
|------------------------------|---------------|
| Density                      | 2550kg/m³     |
| Specific heat capacity       | 790J/kg.K     |
| Heat transfer coefficient    | 0.749w/m.K    |
| Soften point temperature     | 719°C         |
| Annealing point temperature  | 550°C         |
3. The Numerical Simulation

In order to analyse the change of the surface shape of the mirror after the gradient temperature forming, this research simulated the process of spin-casting of the bifocal mirror. The H-K9L optical glass, which has stable properties at room temperature and is not prone to phase separation and crystallization in the melting state, was selected as the experimental material in the simulation. The material parameters are listed in Table 1.

In the simulation, the same geometric dimension of the mould and the same height of the liquid pool as that in the experiment were used for modelling, and the modelling result is shown in Figure 2. Because the simulation mainly studied the liquid level change of the glass melt in the spin-casting process, the VOF two-phase flow model which is good at analysing the free-liquid surface was selected for calculation. The moulding temperature of the mirror in the simulation was 860°C, and the viscosity of the glass was 2000Pa·S. There are two kinds of fluid flow: laminar flow and turbulent flow. Under the adopted moulding temperature, the glass melt is an ultra-high viscosity fluid. During the spin-casting, the Reynolds number of the fluid is minimal, which fails to reach the critical value between the laminar flow and turbulent flow. Therefore, the laminar flow model was employed in this simulation.

4. Results and Discussion

4.1. Comparison of the Experimental and Simulation Results

First of all, the first step of the spin-casting was analysed. The rotation speed of the mould was 50rpm, and the simulation result of the liquid level of the glass melt after reaching stable is shown in Figure 3.

When the forming temperature dropped to the point of Tg, the rotation speed of the glass remained unchanged. Moreover, in this cooling process, the cooling shrinkage of the glass was minimal, which can be ignored. It can be assumed that the surface shape of the glass remained unchanged during the first annealing. Therefore, this thermal radiation stage of glass was simulated directly, and the radiation...
temperature was 860 ℃. The temperature field after thermal radiation is shown in Figure 4.

![Figure 4. The temperature field distribution.](image)

Glass is a kind of amorphous material with no fixed melting and solidifying point. In the simulation, it is assumed that when the temperature is lower than the softening point of glass, the glass is solid and does not have fluidity; when the temperature is higher than the softening point, the glass is liquid and has fluidity. Figure 5 represents the distribution of the solid and liquid phase of the glass.

![Figure 5. The distribution of the solid and liquid phase of the glass.](image)

Since the height of the insulation wall is lower than the liquid level, there will be a heat-affected zone above the insulation wall (see the enlarged view in Figure 6). Due to the heat transfer of the inner surface, in which the temperature is higher than the softening point of glass, some of the fluid flows under the action of the force. The blue part in Figure 7 is the zone of the solid phase. The glass in the solid phase zone maintains a constant temperature in the constant temperature processing, which is lower than the softening point of the glass. The glass will not melt or deform in spin-casting. Thus the model of the second step of spin-casting could be simplified (see in Figure 7).

![Figure 6. The enlarged view of the heat-affected zone.](image)
Using the simplified model, this research conducted the simulation for the second step of spin-casting forming. A rotation speed in the second step was set as 90rpm. In the process of rotation, the surface curvature of the inner glass melt increased gradually under the centrifugal force. The glass melt spread outwards after breaking through the surface tension. The contact temperature between the fluid spreading outwards and the solidified part of the outer decreased gradually, and meanwhile, the fluid also solidified gradually. When the fluid spreading out completely solidified and the spreading stopped, the liquid level reached a stable state. As the simulation result is shown in Figure 8, the distance of inner fluid spreading out is about one-third of the outer surface.

Figure 7. The simplified model.

Figure 8. The simulation result.

Figure 9(a) shows the experiment result of the bifocal mirror forming. CMM was used to measure the surface shape of the mirror blank obtained in the experiment, and the measurement result was compared with the simulation result of the surface shape, as shown in Figure 9(b). Through the comparison, the maximum deviation of between the data obtained in the experiment and that in the simulation is 6.5μm, the curved surface processed in the experiment is consistent with the prediction of the trend of shape change in simulation. Therefore, the simulation result can be used to predict the surface shape of the mirror blank processed in spin-casting.

Figure 9. The comparison between the experimental data and the simulation data and their deviation.

4.2. The Simulated Analysis of the Junction Position and that after Changing the Position of the Heat Insulation Wall

Based on the above analysis of the surface shape of the formed bifocal mirror blank, the junction position of the inner and outer surfaces after material removal is obtained by drawing the curve. Although the curvature of the inner and outer surfaces of the mirror blank processed by this method can reach the
expected value, the junction position deviates. The expected junction position between the inner and outer surfaces is the position of the heat insulation wall set in the experiment. However, the simulation and experimental results show that this position is smaller than the radius of the insulation wall. For a bifocal mirror, the accuracy of the junction position between the inner and outer surfaces is an extremely important parameter. Therefore, the accuracy of the junction position needs to be improved by adjusting the position of the heat insulation wall.

In order to solve the problem of the deviation of the junction position, this research simulated and analysed different junction positions formed by different position settings of the insulation wall. The parameters of the simulation shown in Table 2.

| The location of insulation wall (mm) | The rotation speed of first step (r/min) | The rotation speed of second step (r/min) |
|--------------------------------------|----------------------------------------|----------------------------------------|
| 1 25                                  | 50                                     | 90                                     |
| 2 27.5                                | 50                                     | 90                                     |
| 3 30                                  | 50                                     | 90                                     |
| 4 32.5                                | 50                                     | 90                                     |

Under the same rotating speed, the simulation results of spin-casting with different position settings of insulation wall shown in Figure 10. In this Figure, the four vertical lines with the colour of red, blue, green and purple respectively represent the different positions of the heat insulation wall. The four colour curves respectively represent the different surface shapes formed with the different positions of the heat insulation wall. The black line is the curved surface formed in the first step of spin-casting. The upper part of the blank line is the part to be removed after the final forming. The colour points A, B, C and D are the junction positions of the inner and outer circles, respectively.

**Figure 10.** The different junction positions of the inner and outer surfaces between the insulation wall and the centre point.

The result verifies that the junction position of the inner and outer surfaces can be compensated by changing the position of the insulation wall. Figure 11 shows the positional deviation. With the same rotating speed in spin-casting, the farther the insulation wall is from the centre of the mirror, the larger the diameter or the inner surface of the mirror. The expected radius of the inner surface is 25mm, the distance between the position of the heat insulation wall and the centre point changes from 25mm to 30mm, and the deviation of the junction position is reduced from 4.385mm to 0.717mm. When the distance continues to increase to 32.5mm, the deviation of the junction position becomes -0.932mm. Therefore, when the position of the insulation wall is in the range of 30mm and 32.5mm, the deviation of the junction position of the surfaces has the minimum value.
Figure 11. The deviation between the position of the insulation wall and the junction position of the surfaces.

By setting the insulation wall between 30mm and 32.5mm, simulations were carried out with every increase of 0.1mm. The deviation curve between the position of the insulation wall and the junction position of the surfaces obtained in the 25 times of simulations is shown in Figure 12. Through the data analysis, when the position of the insulation wall is set at 31mm, the deviation of the junction position is 0.04mm; when the position of the insulation wall is set at 31.1mm, the deviation of the junction position is 0.0086mm.

Figure 12. The deviation between the position of the insulation wall and the junction position of the surfaces (30-32.5mm).

As the compensation results can not reach the desired compensation accuracy, the value range of the position of the insulation wall is thus reduced continuously through the iterative calculation in the simulation. By calculation, the position of the heat insulation wall that meets the processing requirement is obtained, and the purpose of compensating the deviation of the junction position is achieved. By setting the insulation wall between 31mm and 31.1mm, simulations were carried out again with every increase of 0.01mm (see the simulation results in Figure 13). The results show that when the heat insulation wall is at 31.08mm, the deviation is the smallest of 2.15μm, which meets the requirement of deviation of the junction position. Then the experiment was conducted with this data to form the bifocal mirror, and the junction position deviation was measured as 3.76μm, which verifies the feasibility of this method.
Figure 13. The deviation between the position of the insulation wall and the junction position of the surfaces (31-31.1mm).

5. Conclusion
In this research, experiments and simulations were carried out to analyse the surface change of bifocal mirror in the process of spin-casting forming, and the effectiveness of the simulation results for the prediction of the surface shape of the mirror blank is verified by comparing the simulation results with the experimental results. In the experiment, it is found that there was a significant deviation between the junction position of the curved surfaces and the expected one. Therefore, through the iterative calculation of the shape changes of the mirror blank, the different deviations of the junction position of the surfaces with different positions of the insulation wall were compared, reducing the value range of the position of the insulation wall to make the deviation decrease gradually. By setting the position of the heat insulation wall to 31.08mm in the forming experiment, the deviation of the junction position decreased from 4.358mm to 3.76\(\mu\)m, which was reduced to the micron level. Therefore, it is feasible to use the way of simulated calculation to compensate for the deviation of the junction position of the curved surfaces of the bifocal mirror.

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