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Residual stress in the annealing process of centrifugal casting aspheric mirror

The application of aspheric mirror becomes widely available, but most of our demands for aspheric mirrors still depend on the foreign countries, which is not conductive to the development of optoelectronics field in China. Therefore, it is imminent to conduct a study into aspheric mirror. In this thesis, centrifugal casting theory and simulation system are used to study the residual stress in the annealing process of aspheric mirror, facilitating to analyze the influence of annealing rate, annealing retention force and casting temperature on residual stress. This provides an important reference for actual production based on the experimental results and further promotes the follow-up experimental research.

Key words: *Centrifugal casting; annealing; residual stress; aspheric mirror.*

1. Introduction

The application of aspheric optic components becomes widely available and the application of optical devices is also increasing. In the optical system, aspheric optics can improve the accuracy of optical instrument. In addition, it can simplify the structure of optical system and help to reduce the weight and size of the instrument, which is good for system's quality and accuracy. At present, the application of aspheric mirror is inseparable from the development of various types of high technologies, such as digital cameras in the optical communication and car cameras in auto photoelectric, which requires a high resolution. Aspheric mirror, with a good development aspect in these fields, plays an important role in promoting the optical manufacturing technology [1]

In spite of a good prospect, aspheric mirror is still underdeveloped in China. At present, most of aspheric mirror used by optoelectronic products in China are not made in home, for example, the commonly used lenses of CD, DVD, etc. According to statistics, as of 2015, there was requirement of 4 billion aspheric mirrors in measuring instrument, 3.6 billion in manufacturing, 4 billion in medical technology, 8 billion in information technology and 7.6 billion in optoelectronics. In addition, there is also a great demand for aspheric mirror in other fields, which is increasing every year. Based on that, we can see the aspheric mirror will be widely used. Therefore, to vigorously improve and develop the manufacturing of aspheric mirror, not dependent on foreign countries, will largely reflect the improvement of science and technology in China [2]. In the past, the processing of aspheric mirror usually had two steps, namely, roughing and finishing. Roughing is to process glass blank by using silicon carbide, removing its surface material. However, with a high roughness, the quality is unsatisfactory after the processing. Finishing, based on the roughing, is a further processing of glass surface after the roughing, so it is equipped with higher quality. Relatively speaking, foreign aspheric mirror processing technology takes the leads in the world. The aspheric mirror can be processed in one time to obtain the finished product meeting the requirement and reduce its processing time as well as improve the processing efficiency. Therefore, the research of centrifugal casting aspheric mirror and analysis of residual stress play an important role in promoting the mature processing of aspheric mirror in China.

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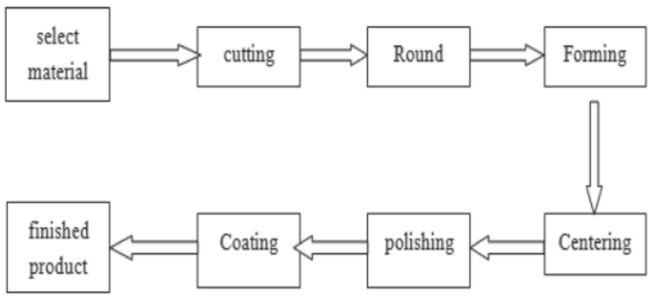

Fig.1 Traditional aspheric mirror processing flow

2. Equipment and experiment

See Fig.2 and Table 1.

3. Centrifugal casting and residual stress

3.1 Centrifugal casting

With a long history, centrifugal casting emerged in the thirties of the last century. In sixties, it was applied in producing the roll and countries had mastered the technology

Fig.2 Centrifugal casting system and control cabinet

TABLE 1: SYSTEM PARAMETER

Parameter name	Specific data
Maximum heating temperature	1200°C
Furnace temperature uniformity	≤±5°C
Furnace temperature stability	≤±1°C
Heating time of empty furnace	≤2h
Rotating speed	15~120 r/minl continuously adjustable
Furnace lifting height	700 mm
Furnace size (D * H)	φ 650×460 mm
Table size (D * H)	φ 160×150 mm
Overall dimensions (L * W * H)	650×650×1100 mm

in seventies. Centrifugal casting is generally applied to the ordinary alloy steel roll. After two pouring, the cold and hard surface of high alloy and the alloy core material can be effectively combined, thereby improving the wear resistance of finished products. The centrifugal casting is featured by low cost, relatively easy-to- master process and good finished product performance. And along with over 80-years history, it is equipped with a mature technology [3].

3.2 Introduction to residual stress

The quality of finished product is inseparable from the organizational factors as well as its own residual stress. Residual stress is produced during the processing and manufacturing, which is attributed to the unstable temperature and organization and uneven deformation in the processing of finished products, leading to a balance result. That is to say, there is a non-uniform stress in the finished product and it is in the range of its own equilibrium stress. Residual stress is mainly caused by the uneven deformation brought by external force and temperature changes. There will be more or less residual stress in the process of manufacturing workpiece. Generally, residual stress is divided into two parts: the macro-stress and the micro-stress. Macro-stress refers to the equilibrium stress of the entire object. For example, when the metal with a large volume solidifies, its size will change. Therefore, the corresponding macro-internal stress will be produced during the solidification, thus releasing the macroscopic residual stress that leads to the change of size. Micro-stress refers to the residual stress produced in the equilibrium region of grain size [4]. The microscopic residual stress will change the macro size after the releasing, but the release of stress inside the atom will not affect it. Macro-stress and micro-stress share some certain connection, but there are also some differences between them.

3.3 Influence of residual stress

The effect of macroscopic residual stress is equivalent to that of external force. If there is tensile residual stress on the surface of the object, its hardness is lower; if there is compressive residual stress, its hardness is relative higher. The compressive residual stress on the surface of the parts can improve the fatigue strength of the part and prolong its life. The main reason is that the residual stress may weaken the external load ability, thereby improving the part's fatigue performance. However, when the parts are subjected to uniform stress, the presence of residual stress is not advantageous. The main reason is that the unfavorable stress will more easily force the material to yield, accelerating the damage to fatigue fracture and stress corrosion fracture [5]. Nevertheless, the formation and initial development of the crack are related to the micro-residual stress. From the perspective of micro level, the formation of crack requires a high concentration of stress and its development also needs certain stress intensity, which is prevalent in the materials of micro-stress. There is a certain amount of energy in the stability of residual stress. With an uneven distribution, these energies lower the stability of material, resulting in accelerated reaction of material. Residual stress in the residual material is more susceptible to corrosion cracking and wearing, so the microscopic residual stress cannot be ignored. It tends to have a great impact on the performance of the material, which is not conductive to its application.

During the casting and cooling process, the formation of residual stress is the combined effect of stress caused by the influence of uneven heating, component size and techniques on material structure and components. The fatigue strength, corrosion and precision of the workpiece can be affected by the residual stress changes [6].

3.4 Cause of residual stress

The effect of the residual stress is introduced above: residual stress exists in the component so that the life span of the component is shortened and fracture is easily happening to components, thus resulting in the production of finished products. In this context, the causes of residual stress must be effectively analyzed, in order to reduce and lower the production of residual stress and improve the productivity. Uneven elasticity and plastic deformation are the main causes of residual stress. In any process, there is always a reason for the generation of residual stress. In addition, the generation of residual stress is also related to the temperature, casting stress, phase change, mechanical obstruction, uneven deformation in the production and the distortion between different multiphase alloys [7]. More specifically, in the production, the components are cooled from high temperature during casting, so that different parts of the components are cooled unevenly, thereby resulting in residual stress. This is thermal stress formed during the expansion and shrinkage of components caused by time difference that are brought by the different parts' cooling. When the components are solidified and cooled, there will be a corresponding line shrinkage, which may change the volume of the components. In the process of volume changes, stress will be generated. This is casting stress. And during the mental transformation, there will be more or less differences in specific volume between new phase and parent phase, resulting in a corresponding stress changes. Attributed to the different specific volume, the direction of residual stress and thermal stress are also different, thereby generating residual stress on the surface of the mental. Materials and cooling condition are the main factors affecting the strength and distribution of transformation stress. The casting and cooling of workpiece will be obstructed mechanically, resulting in a corresponding mechanical barrier stress. In addition, there are also important factors that affect residual stress, such as the line shrinkage coefficient of the alloy, the elastic modulus of the metal and the thermal conductivity of the alloy. And the uneven deformation of the parts will also produce residual stress [8].

3.5 Residual stress relief method

During the casting, there are many factors that result in residual stress, which may cause danger to the quality of the components and finished products. Therefore, to eliminate or reduce the residual stress has a great significance to improve the production efficiency and quality of finished products. To release residual, mechanical methods can be used to deform the interior of the parts, so that the residual stress is dispersed and the concentrated stress is eliminated. However, the mechanical method, used for macro-stress only, cannot eliminate the micro-stress [9]. The fundamental way to eliminate and reduce residual stress is to minimize the stress in the casting process, as shown in Fig.3, which are common methods for the residual stress relief.

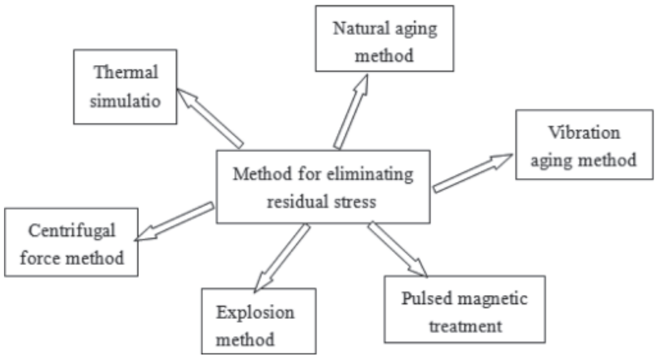

Fig.3 Residual stress relief methods

4. Simulation experiment of aspheric mirror centrifugal casting

In the annealing process of centrifugal casting, glass lens temperature gradually shifts from the transition temperature down to room temperature and internal structure of glass is slowly relaxed. The residual stress must be minimized when the glass is formed, because refractive index of the lens is affected by the residual stress, thereby leading to a decrease in the forming quality. The degree of glass structure relaxation has a great relationship with residual stress, and affects the volume and shape of the lens at the same time. In the transition temperature range, if the temperature suddenly changes, the glass volume will be changed suddenly. This is structure relaxation phenomenon [10]

4.1 Analysis of annealing parameters

The annealing of centrifugal casting aims at coupling the residual stress produced by relaxing the pressure so that the stress relaxation after the annealing of glass will not happen again. The distribution of refractive index is decided by the stress state after annealing and a large stress will lead to a broken glass. Annealing rate is the main processing parameter in the annealing process. In the finite element software, the annealing parameters are adjusted to boundary conditions and initial conditions. According to the structure relaxation theory, relevant physical values are given to make coupling analysis, thus obtaining the final result. This thesis is to analyze the aspheric mirror stress in different annealing process based on the different processing parameters, so as to determine the reasonable processing parameters to facilitate the actual production.

Fig.4 Finished product

annealing process, a higher temperature of centrifugal casting will accelerate the particle movements in aspheric mirror, thus resulting in a better flow of particles and faster relaxation. Therefore, it can be judged that the centrifugal casting temperature can effectively reduce the residual stress of aspheric mirror.

4.3 Influence of annealing retention

During annealing in centrifugal casting, an annealing retention force is applied to the bottom of the module to preserve the shape of the mold and to be fully copied onto the aspheric mirror. The research of annealing retention has a certain relationship with the residual stress of the aspheric mirror during the annealing. In this context, appropriate processing parameters can be selected to facilitate actual processing and production. The processing parameters are set and kept the same as follows: Ua = 2ºC/s, Tm = 580ºC, Vm = 0.2mm/s; consistent with the previous analysis factors, the friction coefficient is set at 0.4μ; in addition, different annealing retention force are set. It shows that there is no connection between the residual stress in the annealing and annealing retention. Table 3 describes the values of four grops of different annealing retention forces.

Centrifugal casting of aspheric mirror requires a setting of an initial condition in which the initial condition in the annealing process are input to the model under study and the temperature at which the annealing is completed is set at 500ºC. In order to study the stress state affected by annealing rate after the annealing, this thesis sets the annealing rate- 1?/s, 1.5?/s, 2?/s, 2.5?/s and 3?/s respectively. In addition, the residual stress change of aspheric mirror after annealing under different parameters is also studied, as well as the annealing time affected by the annealing rate. Annealing time refers to the shortest time of even temperature distribution when the aspheric mirror shifts from the upper limit of the transition temperature to the lower limit (T1). The temperature range of the subject is 800ºC, which aims at studying the centrifugal casting temperature, annealing retention and the influence of annealing rate on residual stress [11].

4.2 Influence of casting temperature

During the annealing of centrifugal casting, the aspheric mirror structure is relaxed, as well as the residual stress. The residual stress of aspheric mirror after the annealing basically remains stable. That is to say, when the temperature decreases from T1 to room temperature, the residual stress almost stays the same. In order to study the effect of casting temperature on the residual stress during annealing, three groups of temperatures are set at 560ºC, 570ºC, 580ºC respectively. The other processing parameters stays the same, namely, Fa = 600N, Vm = 0.2mm/s, Ua = 2ºC/s and friction coefficient is 0.4. Table 2 shows the numerical contrast of residual stress in centrifugal casting and annealing.

As can be seen from the Table 2, in the aspheric mirror

TABLE 2: RESIDUAL STRESS VALUES IN ANNEALING PROCESS AT DIFFERENT TEMPERATURES

Casting temperature (ºC)	560	570	580
Residual stress (MPa)	12.000	6.000	2.000

TABLE 3: RESIDUAL STRESS VALUES IN ANNEALING PROCESS UNDER ANNEALING RETENTION

Annealing retention (N)	200	500	800	1000
Residual stress (MPa)	6.521	6.522	6.522	6.522

When the annealing retention force is 200 N, the residual stress is 6.521 MPa; when the annealing retention force is 500 N, the residual stress is 6.522 MPa; when the annealing retention force is increased to 800 N and 1000 N, the residual stress stays the same with when the retention force is 500 N. When the annealing retention force increases from 200N to 500 N, 800 N and 1000 N, the change of residual stress still stays within 0.001 MPa. Therefore, it can be concluded that there is no connection between annealing retention force and residual stress in the annealing process.

4.4 Influence of annealing rate

The main processing parameters in the annealing stage are the annealing rate and annealing retention force. In this study, the effect of annealing retention on the residual stress during annealing is not obvious. And in the annealing process, the annealing rate is adjusted by the temperature an flow rate of nitrogen, so it can be seen that the annealing rate, annealing time and the residual stress during the annealing are inextricably linked. By changing the annealing rate, namely the temperature time, the influence of residual stress can be judged. During the annealing process, the aspheric mirror structure is relaxed, as well as the residual stress. Therefore, it can be judged that the longer the annealing time is, the smaller the rate will be and the more relaxed stress will be. However, as a kind of guess and judge, it also needs to be proven by experiment. For the experiment, the parameters should be set to carry out a simulation experiment: Fa = 600 N, Tm = 580^{o}C, Vm = 0.2 mm/s and friction coefficient μ is 0.4. The experimental results are shown in Table 4.

As can be seen from Table 4, when the annealing rate is in the range of 1 to 2.5^{o}C/s, the residual stress will be decreased as the annealing rate increases, which is contrary to the original guess.

Table 4: Residual stress values in annealing process under annealing rate

Annealing rate (/S)	1	1.5	2	2.5	3
Residual stress (MPa)	6.25	6.28	6.33	6.38	6.52

5. Conclusion

In this thesis, the residual stress in the annealing process of centrifugal casting aspheric mirror is analyzed and studied and the results based on the experiment have a great significance to the actual production. Aspheric mirror is widely applied, especially in the application of optics. However, our mastery in this technology is not mature, so the study of aspheric mirror is conductive to the development of optical manufacturing technology in China. This thesis firstly introduces the centrifugal manufacturing and residual stress. Then the development of centrifugal manufacturing is generalized and the generation, influence and relief of residual stress are described in detail one by one. Through the simulation case of aspheric mirror centrifugal casting, three aspects including the centrifugal casting temperature, annealing retention and annealing rate are analyzed, resulting in the corresponding experimental results, which provides the data support for actual production of aspheric mirror. The shortcoming of this project is that the experimental conditions are not comprehensive enough, so the result may be featured by a few mistakes. We hope the follow-up scholars can improve it.

Acknowledgments

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