Research on Lapping Technology for Beryllium Rotor of ESG

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Abstract

In this paper, the process parameters such as the diameter of the cups, the rotation speed of the cups, and the lapping pressure are optimized through the simulation analysis of the lapping process parameters in the four cup lapping action and the analysis of the statics of the beryllium rotor. A four cup lapping platform for a beryllium rotor was built, and the four-axis motion control was realized through a programming method based on LabVIEW. Cups with three surface materials were developed by using vapor deposition and other methods, and lapping experiment were conducted for cups with different materials and granularity. Finally, a beryllium rotor with a surface roughness of 80nm was obtained through the design and processing of the process route, and an ultra-precision lapping process for the ESG beryllium rotor was obtained.

1 Introduction

The electrostatic gyroscope (ESG) is currently the most accurate inertial navigation device. The beryllium rotor is the core component of ESG, and its manufacturing accuracy directly determines the navigation performance of ESG [1–2]. The spherical beryllium rotor is an ultra-precision sphere. The manufacturing accuracy indicators are mainly sphericity and surface roughness. For the processing of this kind of precision sphere, the lapping technology is particularly critical. Four cup lapping technology is the most effective method to obtain ultra-high machining accuracy [3–4]. Therefore, it is necessary to study the four cup lapping technology of spheres.

2 Four Cup Lapping Process Simulation

The basic structure of the four cup lapping machine is that the four axes (the axes of the four cups) form a regular tetrahedron structure. The sphere is located in the center of the tetrahedron. The spatial position of each cup and the sphere is shown in Fig. 1.

The necessary condition to achieve good uniformity in lapping action is that the sphere can be enveloped by the trajectory of four cups. The main influencing factors include speed and diameter of the cups, the duration of each combination of motions, namely the motion cycle. In order to study the four cup motion, it is necessary to simulate the influence of the grinding process parameters on the trajectory of the sphere with a diameter of $\varphi 38\text{mm}$ during the lapping action. During the lapping action, the contact points between the cup and the sphere must be converted to the machine coordinate system through coordinate transformation [6–8]. After constructing the kinematics model, Matlab software was used to simulate and analyze the lapping track under different grinding process parameters.

2.1 Analysis of the cup diameter

Different lap diameters have different enveloping areas. The size of the enveloping area directly affects the time required for the complete envelope of the spherical surface. Therefore, a suitable cup must be selected in lapping action. Figure 2 shows the simulation results of the lapping track under different

diameters of the cups when the rotation speed of the lap is 60r/min and the rotation cycle of is 3 s. The four colored circles represent the contact lines of the four cups and the sphere.

It can be seen from the figure above that at the same rotation speed and rotation cycle, the larger diameter of the cups, the larger lapping envelope area, which is conducive to complete the ball grinding at a faster speed. However, the diameter of the cups should have a maximum value. Since the axis angle of the grind is 109.47° , when the four cups are tangent to each other, the diameter of the grind is the largest.

2.2 Analysis of lapping cups speed

Since the sphere rotates and produces relative motion driven by the four cups friction torque, the rotation speed of the grind determines the speed of the relative motion of the sphere. Therefore, the speed of the cups in the lapping action is one of the main research contents of the lapping technology. Figure 3 shows the simulation results of the lapping track at different rotation speeds of the cups when the rotation cycle of the four axes is 3 s and the diameter of the cups is $\Phi 12\text{mm}$.

2.3 Analysis of lapping cycle

There are six movement combinations for four cup lapping. Each combination can achieve the envelope of the sphere when the time is long enough, but it cannot complete the uniform lapping alone. The uniform lapping of the sphere can only be achieved by periodically adjusting of the movement combination. Therefore, the adjustment cycle of the movement combination has become a key process parameter for a lapping action. Figure 4 shows the lapping results under different cycles when the lapping speed is 60r/min and the cups diameter is $\Phi 12\text{mm}$.

2.4 Static analysis of four cup lapping

The beryllium rotor of the ESG is a thin-walled part. It will inevitably produce a certain deformation due to the uniform force of the four cups during the lapping action. Therefore, it is necessary to carry out static analysis and study the deformation of the sphere under the lapping action which can provide a theoretical basis for the lapping process.

In order to obtain the deformation of the beryllium rotor under different loads through ANSYS analysis, the beryllium rotor sphere and the four cup lapping machine three-dimensional model were constructed through UG three-dimensional modeling. During the ANSYS analysis process, the beryllium rotor adopts the J-C model, and the simulation results are shown in the Fig. 5.

It can be seen from the simulation results that the deformation of the beryllium rotor sphere is about $2\text{ }\mu\text{m}$ under a load of 0.01 MPa, which has exceeded the technical index of the beryllium rotor sphericity of 200 nm. Therefore, for the lapping of the hollow beryllium rotor, other materials must be used to strengthen the rigidity of the thin-walled sphere and reduce deformation.

3 Experiment

3.1 Experiment platform design and development

The three-dimensional structure of the experiment platform was designed and the corresponding experimental system was built to conduct lapping experiment. The frame of the four cup lapping machine mainly includes a table and a column, and the table is made of marble; the linear feed adopts a manual module; the four cups rotation adopts an integrated motor. Figure 6 shows the physical diagrams of four cup lapping machine.

Four-axis motion is the key technology to four cup lapping. The rotation of the shaft is driven by an integrated motor, which is controlled by GTS400 motion control card. The four-axis motion combination and periodic adjustment are controlled by the host computer software based on LabVIEW. Figure 7 shows the user interaction interface of the four-axis motion control system.

3.2 Lapping process experiment

The material used in the rotor of the ESG is metallic beryllium. In order to obtain the lapping process of the beryllium rotor, and study the four cup lapping technology, the characteristics of the beryllium material and the relationship between process parameters and lapping quality must be studied. Therefore, this paper conducted an experimental study on the influence of the surface quality of beryllium rotors under different cup materials, granularity and the other parameters.

3.2.1 Removal efficiency of different materials

In order to study the removal efficiency of different materials for beryllium materials, this paper designs and develops cups of different specifications (the material is steel). The three materials of diamond, SiC and Al₂O₃ are sprayed and vapor deposited on the surface of the cups to obtain cups with different surface materials, as shown in Fig. 8.

By installing the above three kinds of cups on the experiment platform, the removal efficiency of different materials on beryllium materials was studied under the condition of the same other lapping process parameters (cup diameter is $\phi 24\text{mm}$, lapping speed 120r/min, lapping pressure 0.1 MPa). Figure 9 shows the result of the removal efficiency of different materials to beryllium.

3.2.2 Influence of granularity

It can be seen from Fig. 9 that the removal efficiency of diamond is significantly better than Al₂O₃ and SiC. Therefore, this paper further uses vapor deposition on the steel cups to prepare diamond powder films with different granularity (W5–W40). Cups with different sizes of diamond particles were developed, and lapping experiments were carried out for the beryllium rotor. Figure 10 shows the micro-morphology and roughness of the workpiece surface after lapping for 1 hour with diamond cups of different granularity.

It can be seen from Fig. 10 that the smaller the particle size, the better the grinding surface quality of the beryllium rotor. When the diamond granularity is W7, after 1 h of precision lapping, a beryllium rotor with a surface roughness of 80 nm is obtained, as shown in Fig. 11.

However, it must be emphasized that the smaller the granularity is, the lower the removal efficiency is. Therefore, the roughing, semi-finishing, and finishing process routes are adopted in the grinding process. The diamond cups with granularity of W28 is used for rough lapping, Semi-finishing uses cups with granularity of W14, and finishing uses a cups with granularity of W7 to ensure the grinding efficiency on the basis of obtaining a beryllium rotor with excellent surface quality.

3.2.3 Influence of lapping speed and pressure

Lapping speed and pressure are important process parameters in the lapping action. In order to obtain the influence of the lapping speed and pressure on the surface quality of the beryllium rotor, especially the surface roughness, cups with granularity of W7 (diameter $\phi 24\text{mm}$) is used to evaluate the surface roughness of the beryllium rotor under the same lapping time (1 h). Figure 12 shows the surface roughness of a solid beryllium rotor at different lapping speeds (the lapping pressure is 5N) and lapping pressures (the lapping speed is 180r/min).

It can be seen from Fig. 14 that with the increase of the lapping speed and pressure, the surface roughness of the beryllium rotor is lower under the same process conditions. The fundamental reason is that when the lapping speed and pressure are higher, the removal is greater which makes the surface quality of the sphere better.

4 Conclusion

In this paper, through the simulation analysis of the lapping process parameters in the four cup lapping action of the beryllium rotor, the process parameters such as the diameter of the cups, the rotation speed of the cups, and the lapping pressure were optimized. A four cup lapping platform for a beryllium rotor was built, and the four-axis motion control was realized through a programming method based on LabVIEW. Cups with three surface materials were developed by using vapor deposition and other methods, and lapping experiment were conducted under different process parameters. Finally, a beryllium rotor with a surface roughness of 80 nm was obtained through the design and processing of the process route, and an ultra-precision lapping process for the ESG beryllium rotor was obtained.

5 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: Wang Ya-Fei wrote the manuscript; Xiong Xue-Feng was in charge of the project guidance; Guo Liang was in charge of the experiment, Tuo chao was in charge of the measurement, Duan Cong-wu, Deng Chu-quan and Huang Peng assisted with experimental platform construction and debugging.

Competing interests

The authors declare no competing financial interests.

Consent for publication

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Ethics approval and consent to participate

Not applicable

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Figures

Figure 1

The spatial position of each cup and the sphere

Figure 2

Lapping track under different diameters of the cups

Figure 3

Lapping track at different speeds

Figure 4

Lapping track under different motion cycles

Figure 5

Deformation of beryllium rotor under different loads

Figure 6

Four cup lapping machine

Figure 7

User Interface of Motion Control System Based on LabVIEW

Figure 8

Diamond-plated cups

Figure 9

The removal efficiency of different materials to beryllium

a. W28, 60min, Ra0.3

b. W14, 60min, Ra0.2

c.W7, 60min, Ra0.08

Figure 10

The micro-morphology and roughness of the workpiece surface after lapping with diamond cups of different granularity

Figure 11

Beryllium rotor and surface roughness measurement results

Figure 12

Surface roughness of beryllium rotor under different lapping speeds and pressures