Research on sealing ring complex curved surface grinding technology

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Abstract. In order to solve the problem of the precision machining of the complex surface of the hydrodynamic seal ring, the precision grinding equipment is used to grind the complex surface. According to the surface structure of the sealing ring, a grinding mathematical model is established, adopting radial ring stacking method and trigonometric formulas to calculate the grinding wheel center movement trace during precision spot grinding. It can provide a strict theoretical basis for the next ultra-precision grinding experiment. According to the movement track, the numerical control program is compiled, and the grinding test of the seal ring is carried out on the self-developed equipment. During the grinding process, the workpiece and the grinding wheel run smoothly. The seal ring test sample meeting the requirements of the face shape is processed, which solves the technical problem of processing the complex face shape. It provides reliable technical support for the subsequent high-precision processing and universal application of the seal ring.

1. Introduction
The function of a main pump is to provide a driving force for circulating components. Generally, multi-stage series hydrodynamic seal or hydrostatic seal is used to prevent coolant leakage [1-5]. It is one of the important forms of a main pump shaft seal to set up a fluid dynamic pressure seal with a corrugated surface on the outer side of the flat end face of the seal ring. The moving end face of the seal ring is composed of a flat face and an inclined corrugated surface. The intersection curve of the flat face and the corrugated surface is a closed wavy line extending along the circumference direction. The distance between the lowest point of the wave surface and the flat surface is 12 μm, and the wave number is 7. When used in combination with the static ring, a corrugated gap is formed at the sealing interface along the circumferential direction, and a convergent gap is formed along the radial direction. The advantage is the hydrostatic effect produced by the radial convergent gap ensures there is always a liquid film between the sealing interface during shutdown and operation, and the hydrodynamic effect produced by the circumferential corrugated gap ensures the lifting force of the main pump during operation, while the flat surface enhances the leakage control ability. The hydrodynamic seal ring used in the main pump is made of silicon carbide, tungsten carbide and other hard materials. The surface accuracy is required to be less than 0.4 μm, and the surface roughness is less than Ra 1nm. So it is very difficult to make it precisely.

Corrugated surface is a kind of free-form surface in space. Traditional grinding methods, such as surface grinding, cylindrical surface grinding and form grinding cannot meet the machining requirements in grinding kinematic geometry and in the kinematic accuracy of machine tools. The computer-controlled optical surface modification technologies such as air bag polishing,
magnetorheological polishing and ion beam polishing can achieve high-precision processing of optical surfaces, but the processing efficiency is low, and there are edge effect problems when processing the surface of annular parts [6-8]. In view of the machining requirements of the complex profile, a grinding method is proposed, which uses the arc-shaped wheel for high-precision multi axis linkage point contact grinding, high-precision profile modification, high-precision measurement and wear compensation for the diamond wheel. The grinding method has the extensive applicability and practical significance for the precision machining of complex shaped parts in defense systems.

2. 3-D shape of sealing ring
One of the sealing forms of the main pump is the hybrid seal composed of plane sealing ring and conical corrugated sealing ring. What we are going to process is the conical corrugated surface, which is a spatial surface composed of flat surface and conical corrugated surface. It changes along the radial direction according to the cosine curve rule. The following formula is the surface shape equation. The amplitude of the periodic waviness is generally only 2.5-10 μm, and the wave number is generally 5-15. The structure is shown in figure 1 (to highlight the visual effect, the amplitude and cone angle of the waviness are enlarged) and figure 2.

Face shape formula:  
\[ h = \begin{cases} 0 & \text{if } r < r_0 \\ \gamma (r - r_0) [\cos(n \times \theta) - 1] & \text{else} \end{cases} \]

\( r_0 \) is the outer circle radius of the sealing dam, \( \gamma = 0.0003 \sim 0.0005 \), \( n = 5 \sim 15 \).

Specification of sealing ring: outer diameter: 150 mm, inner diameter: 110 mm, diameter of sealing flat: 120 mm, \( \gamma = 0.0004 \text{ rad} \), number of corrugations: 7 (the difference between the highest point and the lowest point is 12 μm).

Technical requirements: surface accuracy: sealing flat surface < 0.1 μm, conical corrugated surface < 0.4 μm (P-V), surface roughness Ra < 1nm.

![Figure 1. 3-D surface structure.](image)

![Figure 2. Sectional view.](image)

3. Establish the mathematical model of seal ring grinding
In the radial direction, the radial radius is divided into a number of \( r \) curves. The spatial shape of the corrugated surface is the continuous integral of the surface to \( r \). The work piece surface equation \( h = \gamma \times (r - r_0) \times [\cos(n \times \theta) - 1] \), \( (r > r_0) \), which is decomposed into several curve stacks of \( r \), as shown in figure 3, when \( r \) is set, the curve equation is the relationship between \( h \) and \( \theta \), and the curve is expanded along the circumference of \( r \), and the thick solid line in figure 4 is represented as the curve graph of arc length \( L \) and \( h \) corresponding to \( \theta \) (to highlight the visual effect, the curve is expanded), and the equation of (L, H) is the equation of wheel path.

From figure 3, let \( L=r \times 0 \), \( H \) is the height of grinding wheel center OS relative to O, so (L, H) is the track of grinding wheel center in LOH coordinate system, the original equation \( h = \gamma \times (r - r_0) \times [\cos(n \times \theta) - 1] \) is shifted upward by \( 2\gamma \times (r - r_0) \), and the original equation in LOH coordinate system is obtained:

\[ h' = 2\gamma \times (r - r_0) + \gamma (r - r_0) \times \left[ \cos \left( n \times \frac{L}{r} \right) - 1 \right] = \gamma (r - r_0) \times \left[ \cos \left( n \times \frac{L}{r} \right) + 1 \right] \]
According to the geometric relationship in figure 3, the equation of grinding wheel center (L, H) is derived:

$$H = k' + R_s \times \cos \alpha = \gamma \times (r - r_s) \times \left[ \cos \left( \frac{n \times L}{r} \right) + 1 \right] + R_s \times \cos \alpha$$

(1)

where $\alpha$ is the angle between any grinding point A tangent and coordinate L, and $0 < \alpha < \pi$ / 2; $R_s$ is the radius of grinding wheel.

$$\tan \alpha = \left| \frac{dh}{dl} \right| = \left| \frac{\gamma \times (r - r_s) \times \cos \left( \frac{n \times L}{r} \right)}{\gamma \times (r - r_s) \times \sin \left( \frac{n \times \theta}{r} \right)} \right|$$

where $K_A$ is the slope of the curve at tangent point A, so

$$\cos \alpha = \left( 1 + \tan^2 \alpha \right)^{-1/2} = \left( 1 + \left[ \frac{n \times \gamma \times (r - r_s) \times \sin \left( \frac{n \times \theta}{r} \right)}{r} \right]^2 \right)^{-1/2}$$

Take equation (1) and get:

$$H = \gamma \times (r - r_s) \times \left[ \cos \left( \frac{n \times L}{r} \right) + 1 \right] + R_s \times \left[ 1 + \left( \frac{n \times \gamma \times (r - r_s) \times \sin \left( \frac{n \times \theta}{r} \right)}{r} \right)^2 \right]^{1/2}$$

(2)

Taking $L = R \times \theta$ into equation (2), the equation of wheel center track ($\theta$, H) is obtained as follows:

$$H = \gamma \times (r - r_s) \times \left[ \cos \left( \frac{n \times \theta}{r} \right) + 1 \right] + R_s \times \left( \frac{r^2}{2} + \left( \frac{n \times \gamma \times (r - r_s) \times \sin \left( \frac{n \times \theta}{r} \right)}{r} \right)^2 \right]^{1/2}$$

where $\gamma = 0.0004$, $R_0 = 60mm$, $60mm < R \leq 75mm$, $n = 7$, $r_s = 125mm$.

4. Structure of ultra-precision grinding equipment

The equipment adopts the end grinder type structure [9-10], mainly composed of workpiece spindle, grinding wheel axis, Y-axis guide rail, X-axis guide rail, high-precision rotary table, CNC system, etc., as shown in figure 5. Y-axis guide rail, X-axis guide rail and high-precision rotary table can realize numerical control linkage.

The static pressure shafting and guide rail are the main basic parts of ultra-precision machining, in which the runout accuracy of workpiece spindle is $\leq 0.1 \mu m$, the speed range is 0-350r / min; the runout accuracy of grinding wheel spindle is $\leq 0.1 \mu m$, the speed range is 0-1500r / min; the linear motion accuracy of guide rail is $\leq 0.002 \mu m$, the speed range is 0-15000r / min; the static pressure shafting can realize the stable static pressure of 0.0005MPa, in order to ensure the accuracy of grinding.
accuracy of static pressure guide rail is $\leq 0.3\ \mu\text{m} / 300\text{mm}$. A grating ruler is used for precision detection and position feedback of shafting and guide rail, closed-loop control of numerical control system to accurately control linear displacement and angle.

5. Grinding test of sealing ring
The grinding test of the seal ring is carried out on the ultra-precision grinding equipment [11] shown in figure 6.

The circle is separated into several circles whose radius changes continuously in the direction of the radius by the mathematical model of the element face shape. According to the accuracy requirements of the machined face shape, the number of stacked circles is determined. The more the number of separated circles, the closer to the face shape. The whole circumference is divided into 3600 pieces, the workpiece axis rotates slightly to the grinding point, and the wheel axis rotates at 1100rpm. The seal ring is ground by using the arc-shaped wheel to do high-precision multi axis linkage point contact grinding. The workpiece axis is defined as the servo axis, the wheel axis rotates, the X axis feeds to the grinding position, the workpiece axis and the Y-axis interpolation feed. During the grinding process, the grinding wheel runs smoothly without interference.

| Process steps | grinding tool | wheel shaft speed /rpm | workpiece shaft speed /rpm | grinding feed /mm | time /h |
|---------------|---------------|------------------------|---------------------------|------------------|--------|
| Rough grinding | 80° Diamond wheel | 1100 | Servo | 0.005–0.01 | 30 |
| Fine grinding | 120° Diamond wheel | 1100 | Servo | 0.001–0.005 | 50 |

In the experiment, the inductive micrometer is used to detect the sealing ring element on-line, monitor the face shape, and adjust the processing parameters in time, as shown in figure 7.

6. Conclusion
The grinding method of the seal ring is determined by using the self-developed high-precision grinding equipment. According to the space surface structure of the seal ring, the mathematical model of grinding the seal ring is established, and the locus of the grinding wheel center is calculated. In the grinding test of the seal ring, the workpiece and the arc grinding wheel run smoothly without interference, which can complete the precision grinding of the seal ring. The high-precision multi axis linkage point contact grinding solves the technical problem of processing the complex three-dimensional space shape of the seal ring, and provides a reliable technical way for the subsequent high-precision processing and universal application of the seal ring.

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