STRUCTURAL PARAMETER ANALYSIS OF SELF-TIGHTENING METAL U-SHAPED SEAL RING

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ABSTRACT. The effects of different structural parameters on the sealing performance of self-tightening metal U-shaped seal rings were studied. A two-dimensional axisymmetric model of a self-tightening U-shaped seal ring was established using finite element software. The influence of structural parameters such as side wall thickness, bottom wall thickness and boss radius on the sealing performance of the seal ring was analyzed by the control variable method. The results show that as the thickness of the side wall increases, the stress shows a downward parabolic trend, which is the smallest at 0.55 to 0.65 mm; as the bottom wall thickness increases, the stress first increases steadily, and then decreases slowly after 0.8 to 0.9 mm; When the inclination angle is from 0 to 9°, the sealing ring can obtain better sealing performance. The results have guiding significance for the design, optimization and application of subsequent seal ring structures.

1. Introduction
Seals have a wide range of applications. About 90% of machinery requires seals. It involves many disciplines, including mechanics, tribology, materials science, heat transfer, fluid mechanics, and solid mechanics. It is an important guarantee for long-term efficient and safe operation of industrial equipment. In recent years, scholars at home and abroad have conducted a lot of research on various seals, such as labyrinth seals[1], dry gas seals [2-5], brush seals [6], and various seals on centrifugal compressors[7,8], etc. And made considerable progress. Rocket engines using liquid hydrogen and liquid oxygen as fuels are widely used in the aerospace industry, and their severe low temperature and high pressure conditions place high requirements on sealing [9]. The metal sealing ring is the most widely used static sealing structure in the industry. Although its structural size is small compared to the entire equipment, its sealing performance will directly affect the safety of the entire equipment and even the entire system. Metal sealing rings are used in the sealing of aerospace engines because of their advantages such as low temperature resistance and low pressure deformation. However, their disadvantages are high rigidity, difficulty in compression, high pre-tightening force, and high requirements on the surface roughness of the sealing [10-12]. Low temperature and high pressure self-tightening metal static seal, mainly refers to
the use of metal materials and has the characteristics of elastic compensation cold shrinkage deformation structural seals, commonly used structures are metal C-shaped, hollow O-shaped, K-shaped, X-shaped, E-shaped, W-shaped, V-shaped, etc. [13-16]. The sealing features are: small cross-sectional area, low axial load requirements and elastic compensation capabilities. Elastic metal static seals can be manufactured by two methods: mechanical cutting and die spinning [17]. The working principle of the metal seal is that the elastoplastic deformation on the pre-pressure contact surface compensates the gap of the original seal contact surface, and seals the leakage channel to achieve medium sealing [12].

A series of researches on metal seals have been made at home and abroad since the 1970s [18-21]. The domestic research on self-tightening metal sealing rings started late, but the development speed is very fast and the results are significant [22].

2. ESTABLISHMENT OF FINITE ELEMENT MODEL OF SELF-TIGHTENING METAL U-SHAPED SEAL RING

In order to improve the shortcomings of the existing metal seal ring under pressure conditions, poor fatigue resistance, unreliable sealing performance under vibration conditions, combined with the advantages of metal U-shaped ring energy storage and good metal V-shaped ring resilience, A self-tightening metal U-shaped seal ring structure is improved and designed. Its structure is shown in Figure 1.

In recent decades, various metal seal structures have been newly developed in China, such as an improved Y-shaped seal ring that can be applied to both dynamic and static seals [23]; a non-contact type with progressive pressure reduction and throttling discharge functions static seal structure [24], which solves the problem of oil-water separation of the rotating parts of the hydrostatic bearing in a vertical turbine; a seal structure that does not flip during installation and has stable sealing performance during shearing; and an easy-to-install, bearing static sealing structure with strong compression ability and stable sealing performance [25]; Dong Zhang [26] developed two types of static sealing structures with trapezoidal cross-sections to achieve the seal between the metal shell and the window, with a pressure higher than 150 good sealing effect at MPa and temperature higher than 100 °C. Parker [27], as a pioneer in the sealing industry, has developed a variety of sealing structures, of which the BS type sealing structure has two sealing lips that are not sensitive to impact loads; AF type sealing uses the interference fit of the sealing groove and the metal to fix the dust ring in the open groove, and the lip can move with the movement of the piston rod. SSME uses a "U"-shaped pressure-acting sealing element made of silver-plated nickel-based material.

U-shaped seal rings are relatively rare in China. This paper uses finite element software to establish a two-dimensional axisymmetric model of U-shaped seal rings. The model analyzes the structural parameters such as the side wall thickness, bottom wall thickness, and boss radius of the self-tightening metal U-shaped seal ring, and optimizes its structural parameters. The results have guiding significance for the design, optimization and application of seal rings in the future.
The low-temperature and high-pressure self-tightening seal structure has axial symmetry. In order to ensure the accuracy of the structural analysis and reduce the calculation amount, a two-dimensional planar axisymmetric simplified model is established. This model includes a simplified upper flange, a metal seal ring, and a simplified lower flange. The assembly relationship is that the highest point of the upper boss of the metal seal ring contacts the lower boundary surface of the upper flange, and the lowest point of the lower boss and the lower flange. Contact the upper boundary face. Its axial section is shown in Figure 2.

![Fig.1 Geometry Size of U-shaped Seal Ring](image1)
![Fig.2 Simplified Model Diagram of Structure](image2)

### Table 1 Integral Structure Parameter Table

| CATEGORY       | SIZE/mm | CATEGORY       | SIZE/mm |
|----------------|---------|----------------|---------|
| Total Height H | 3.64    | Side Wall      | 0.5     |
|                |         | Thickness δ1   |         |
| Diameter D1    | Φ70     | Bottom Wall    | 1       |
|                |         | Thickness δ2   |         |
| Tilt Angle θ  | 9°      | Boss Radius r  | 0.39    |
| Section Length L1 | 3.64  |                 |         |

The mesh division of the two-dimensional axisymmetric model generally uses a quadrilateral mesh, which can improve the calculation efficiency and obtain accurate calculation results. In this paper, a four-node bilinear axisymmetric reduction and integration unit CAX4R is used to divide the grid. The grid division diagram is shown in Figure 3. The total number of grids is 16565. The grid independence proves that the number of grids is reliable.
Fig. 3 Grid Partition Diagram

In recent years, GH4169 [18] has been widely used in the field of aviation. After research, it has been found that the material has excellent elastoplastic properties under low temperature and high pressure conditions. It is a nickel-based high-temperature alloy with good fatigue resistance, radiation resistance, oxidation resistance, and corrosion resistance in the range of -253 ~ 700 °C. Its approximate grade is Inconel718, which has good processability. The specific parameters of GH4169 material are listed in Table 2.

![Table 2 Material Parameters of GH4169](image)

- Temperature / °C
  -183
  20
- Density / g.cm⁻³
  8.24
  8.24
- Elastic Modulus / MPa
  213000
  203000
- Poisson's Ratio / μ
  0.254
  0.29
- Yield Strength / MPa
  1300
  1030
- Tensile Strength / MPa
  1700
  1270

The working parameters of the U-shaped seal ring are listed in Table 3. The boundary condition labels are shown in Figure 4, and the applied boundary conditions are shown in Table 4. The stress and displacement results obtained by loading in this paper are shown in Figure 5 and Figure 6.

![Table 3 Working condition parameter](image)

| Category                          | Boundary                        |
|-----------------------------------|---------------------------------|
| Internal Pressure Boundary        | N1B1, B1A1, A1G1, G1H1, H1I1, I1J1, J1J2, J2I2, I2H2, H2G2, G2A2, A2B2, B2K2, K2N2 |
Thermal Boundary
Friction Boundary
Frictionless Boundary
Fully Constrained Boundary

Upper and Lower Flanges, Seal Rings
A1B1, B1C1, N1M1, A2B2, B2C2, K2P2
F1F2, O2P2
N2M2

Displacement Constraint Y=0.5mm
K1L1

3. ANALYSIS OF THE INFLUENCE OF VARIOUS PARAMETERS ON THE RESULTS

3.1 Side Wall Thickness $\delta_1$

The thickness of the side wall of the seal ring is mainly to provide the elastic force for the seal ring, but it is connected to the bottom wall thickness and is located at the discontinuity of the structure. It is easy to break when compressed. This paper analyzes the influence of the side wall thickness $\delta_1$ on the mechanical properties of the seal ring as shown in Figure 7.

Fig. 5 Structural stress nephogram
Fig. 6 Structural displacement nephogram

(a) (b)
It can be seen from Fig. 7 that as the sidewall thickness increases, the maximum Mises stress appears as a parabola, which is the smallest at 0.55 ~ 0.65mm; the maximum displacement decreases; from (b), it can be seen that as the sidewall thickness increases, the axial stiffness of the seal ring increases. And the graph (c ~ d) can be obtained from the compression rebound curve. The increase ratio of the self-tightening force decreases as the thickness of the side wall increases. As the thickness of the side wall increases, the stiffness becomes larger. The axial force increment of the position decreases, the self-tightening incremental ratio gradually decreases, and the self-tightening effect decreases. The total amount of self-tightening deformation increased, and the self-tightening effect increased. The rebound rate is reduced and the resilience of the seal ring is reduced. That is, as the thickness of the seal ring increases with the increase in the thickness of the side wall, the rigidity increases during pre-tightening, the self-tightening effect in the working state decreases, and unrecoverable deformation increases, resulting in a decrease in the elasticity of the seal ring. Therefore, the optimal value of the side wall thickness should be selected between 0.4 and 0.45 mm.

3.2 Bottom Wall Thickness δ2

When the bottom wall thickness is compressed, a large strain is generated. When the seal ring is compressed too much, the bottom wall thickness is easily broken, and it has the effect of absorbing energy and storing energy. In this paper, the influence of different bottom wall thickness on the mechanical properties of the seal ring is calculated, as shown in Figure 8.
It can be seen from Fig. 8 that the maximum Mises stress increases steadily with the increase of the bottom wall thickness, and then decreases at 0.8 mm, and then decreases to 0.9 mm at the previous size. The maximum displacement has a maximum value at 0.8 mm. It can be seen from (b) that as the bottom wall thickness increases, the stiffness of the pre-tightened seal ring increases. From the compression rebound curve, we can get the graph (c ~ d), the self-tightening axial force increment decreases, and the self-tightening deformation rebound rate decreases. It can be seen that the stiffness of the seal ring under pressure increases, the elasticity decreases, and the self-tightening effect decreases. The rebound rate gradually decreases, and the elasticity of the seal loop decreases. The recommended value is 0.5 ~ 0.6 mm.

3.3 Boss Radius r

In the design of the structure, a boss using spherical contact at the position of the contact point of the seal ring is selected. In order to ensure the line contact of the seal surface, when a smaller contact force is provided, a larger contact pressure can also be generated to increase the sealing effect. However, the radius of the boss cannot be increased indefinitely. It is directly connected to the thickness of the side wall of the seal ring. When the seal ring is too small, it is easy to detach the upper contact surface when the seal ring is rotated by the compressed side wall and make the flange directly with other contact at non-preset sealing surfaces. This not only causes a waste of the structure of the seal ring, but if other contact surfaces do not guarantee sufficient surface roughness of the contact surface, the seal will leak. However, the boss must not be too large. When its radius is too large, a weak point of stress may occur in the thick middle part of the sealing sidewall connected to it. During the compression process, the sealing ring is broken before it has sufficient sealing force. This paper calculates the influence of the boss radius on the mechanical properties of the seal ring, as shown in Figure 9.
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Fig. 9 Mechanical Property Curve of Seal Ring when r changes

It can be seen from Fig. 9 that the maximum Mises stress of the seal ring is smallest at 0.39 mm with the increase of the boss radius, and the rest is basically near the yield limit. The overall trend of maximum displacement increases; the axial stiffness of the seal ring increases; from the compression rebound curve it can be obtained that (c ~ d), the self-tightening axial force increase of the sealing ring decreases slowly and then decreases sharply, while the rebound rate of self-tightening deformation slowly increases, and the rebound rate decreases first and then increases. Decreased, there is a maximum at 0.35mm. Considering the comprehensive mechanical properties, the best range is 0.31 ~ 0.33mm.

3.4 Tilt Angle \( \theta \)

The inclination angle of the seal ring can directly affect the elasticity of the seal ring when it is compressed. This paper calculates the influence of the inclination angle on the mechanical properties of the seal ring, as shown in Figure 10.
Fig. 10 Mechanical Property Curve of Seal Ring when $\theta$ changes

From Figure 10, it can be seen that with the increase of the tilt angle, the maximum Mises stress increases faster and reaches the yield limit slowly after 9°; the maximum displacement has a maximum abrupt value at 15°, which generally increases; the axial stiffness increases; From the compression rebound curve, we can get the graph (c ~ d). The self-tightening force increase ratio is generally reduced, and has a maximum value at 10° and 20°, while the self-tightening deformation recovery amount gradually decreases, and at 20° there is the minimum value; the rebound rate increases first and then decreases rapidly, and the resilience performance increases first and then decreases. The best result is 0 ~ 9°.

4 CONCLUSIONS

(1) By using the control variable method, a range of values for each structural parameter is obtained when the self-tightening metal U-shaped seal ring achieves better sealing performance.

(2) It can be known from the research results that with the increase of the thickness of the side wall, the stress shows a parabolic trend, which is the smallest at 0.55 ~ 0.65mm; as the bottom wall thickness increases, the stress increases steadily first, and then decreases slowly after 0.8 ~ 0.9mm; As the radius of the boss increases, the stress of the seal ring is the smallest at 0.39mm, and the rest is basically near the yield limit; the sealing angle is better when the inclination angle is 0 ~ 9°; the maximum Mises overall as the outer diameter increases showing a growing trend.

(3) According to the research results, it is known that the thickness of the side wall has a great
influence on the maximum Mises stress and the maximum displacement of the self-tightening metal U-shaped seal ring.

(4) According to the research results, it can be known that the bottom wall thickness and cross-section length have a greater impact on the rebound rate of the self-tightening U-shaped seal ring.

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