ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-THPPP029

TECHNOLOGIES CONCERNING METAL SEALS OF THE UHV SYSTEM FOR ACCELERATORS

H. Y. He, L. Liu, P. C. Wang, Y. S. Ma, B. Tan, Institute of High Energy Physics, Beijing, China

Abstract

Reviewed the domestic research on structural design and sealing function principle of the metal seals, wildly used in the Ultra High Vacuum (UHV) system for accelerators. Analysed and summarized the key technologies concerning the material, contact forms, machining process and test methods of sealing performance. The study will become the basis of designing, machining and quality measuring for the ultra-vacuum metal seals. It provided the foundation for generating seals standards to promote the development of vacuum technology application.

Introduction

V The metal sealing ring is a key sealing component of the accelerator ultra-high vacuum system, achieving a detachable metal to metal end face seal. Ultra-high vacuum systems such as the Beijing Positron and Negative Electron Storage Ring, Spallation Neutron Source, and High Energy Synchrotron Radiation Light Source in China have sealing rings that provide high-temperature degassing and baking at 300 °C, long-term radiation corrosion protection, and almost no penetration of small molecule gases during use. Traditional sealing rings cannot perform well under these harsh working conditions [1]. Metal sealing rings have been widely used in the field of ultra-high vacuum systems, and products with cross-sectional shapes such as O-shaped sealing rings, C-shaped sealing rings, and Δ knife edge sealing rings have reached the practical stage. The C-shaped sealing ring optimized from the basic O-ring, with the C-shaped opening facing towards atmospheric pressure, forms excellent self-sealing; At the same time, the Δ knife edge sealing ring utilizes the advantage of good plastic flow of soft metal to help compensate for the concave and convex gaps and scratches on the surface of the sealing end face, and prevent leakage [2]. At present, stable and reliable ultra-high vacuum metal sealing rings are mainly provided by foreign companies in fields such as accelerators, nuclear power, aerospace, and shipbuilding in China, such as GARLOCK in France and VAT in Switzerland. Due to technological lockdowns, domestic researchers can only obtain partial performance information about metal sealing rings through product manuals. The lack of systematic sealing theory and product standards has hindered the development of ultra-high vacuum metal sealing ring technology in China.

By analysing the research status of ultra-high vacuum metal sealing rings in China in recent decades, this paper summarizes the sealing contact forms, metal materials, and sealing leakage rate measurement methods, explores key issues of structural design optimization and material simulation, forming and processing methods, and sealing performance measurement technology, laying a foundation for establishing a theoretical system of ultra-high vacuum metal sealing rings and promoting engineering applications.

Classification of Metal Static Sealing Materials and Structures

Seals can be divided into two categories: static seals and dynamic seals. The main application of ultra-high vacuum metal sealing is the static sealing of detachable flange connected circular vacuum pipelines. Under external loads, the metal material undergoes plastic deformation and flow to compensate for the gap between the joint surfaces, making it smaller than the diameter of the gas molecules, forming an interface blockage and achieving effective sealing.

The materials and structures of metal sealing rings complement each other, and the research and optimization of materials and the development of finite element simulation analysis have driven the design and development of sealing ring structures. The working performance of metal sealing rings varies with changes in material, geometric shape, and wall thickness.

According to the sealing principle, the material of metal sealing rings is generally required to have certain compression deformation ability, strength, rigidity, rebound ability, and creep resistance. The earliest Baker Hughes Z seal, Caledyne CMTM seal, and Owen X-PAN seal designs used stainless steel, copper, and aluminum sealing rings, which generate radial rebound and expansion through cross-sectional compression. The sealing technology is widely used in industries such as motivation and petroleum. In recent years, with the increasing demand for scientific research and vacuum technology, sealing technology for covering soft metals with high compressive strength and tensile rate metals such as Inconel nickel alloy and Nimonic alloy has become one of the research hotspots. High strength and stiffness represent greater resistance to deformation, allowing for a more stable and reliable vacuum seal with the same sealing force. In addition, the basic requirements for ultra-high vacuum metal sealing rings are the gas release rate and permeability of the metal material. Choose materials with low adsorption, diffusion, and permeability to prevent interface cracks and isolated voids, which are more suitable for obtaining and cleaning extreme vacuum. In addition, the flange and flange locking chain in the accelerator ultra-high vacuum system are made of carbon steel materials such as stainless steel 316L with low magnetic permeability. Therefore, the working pressure of the metal sealing ring should be less than 98 MPa for high-pressure sealing [3].

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-THPPP029

According to the width of the sealing surface, metal sealing rings are mainly divided into three structural types: flat gasket seal, line seal, and lip seal. Ideally, the reliability of metal seals is independent of the width of the sealing surface. However, in practical situations, increasing the width of the sealing surface requires increasing the sealing pressure. With the improvement of mechanical processing capabilities, a large number of ultra-high vacuum systems in accelerators currently use line seals with small contact widths and lip shaped composite structures that utilize ambient atmospheric pressure to assist in self sealing [4]. The contact form of the sealing ring can also be divided into two basic contact forms based on the stiffness of the contact surface: rigid, soft, and flexible. One or two of the contact surfaces are treated as rigid bodies, and the other contact body with much smaller relative stiffness is used as deformable bodies, sacrificing the deformable body to provide plastic deformation blocked by the metal interface. Many ultra-high vacuum metal sealing rings and flange contact can be summarized as rigid flexible contact. Covering the surface of a high tensile strength metal matrix with well plastic flowing soft metal, the composite mechanical properties help block interface leakage and form a more effective ultra-high vacuum seal. At the same time, the sealing ring is usually used as a flexible body in contact alignment to achieve metal to metal sealing, which is more conducive to the replacement and maintenance of vacuum equipment.

Structural Design and Simulation Analysis of Ultra High Vacuum Metal Sealing Ring

Assuming that the sealing ring provides all plastic deformation to compensate for the concave and convex gaps on the joint surface, the final target parameters required for structural design are the sealing ring compression amount and interface contact stress. The core structural dimensions of the flange in the sealing structure include the inner diameter d1 of the sealing ring groove, the outer diameter d2 of the sealing ring groove, and the flange gap d3 (designed maximum compression); The core structural dimensions of the sealing ring are the inner diameter D1 of the sealing ring, the center diameter D2 of the sealing ring, and the height D3, as shown in Figure 1 (b). Generally, the inner diameter d1 of the sealing groove is calculated based on the size of the vacuum pipeline that needs to be sealed, and then the other dimensions above are designed.

The size relationship of the sealing ring structure can be summarized as follows:

$$L = h \times \mu \quad (1)$$

$$d1 = D_2 - H/2 - L/2 - d_0 \quad (2)$$

$$d2 = D_2 + H/2 + L/2 + d_0 \quad (3)$$

H is the longitudinal compression amount, which is between the minimum contact stress at the sealing interface and the failure of the sealing ring due to compression. μ Is the Poisson's ratio, and L is the lateral deformation of the sealing ring. D0 is the design margin, and it is required that when the longitudinal compression amount h is equal to the maximum design compression amount d3, the flange does not hinder deformation to prevent increasing the sealing pressure level [5].

Simulation analysis of sealing ring deformation belongs to large deformation contact analysis. As the compression amount h increases, μ It is no longer a constant. If the change curve of sealing ring material properties is not clear, it shall be determined by sample testing. Set the flange sealing contact surface as a discrete rigid body, set the large deformation material properties of the sealing ring, simulate and analyse the sealing ring structure according to the boundary conditions set in Figure 1 (a), obtain compression and contact stress values close to practical applications, and then complete the final optimization design of the sealing ring structure. Simulation analysis and structural design are not sequential and mutually guide optimization [6].

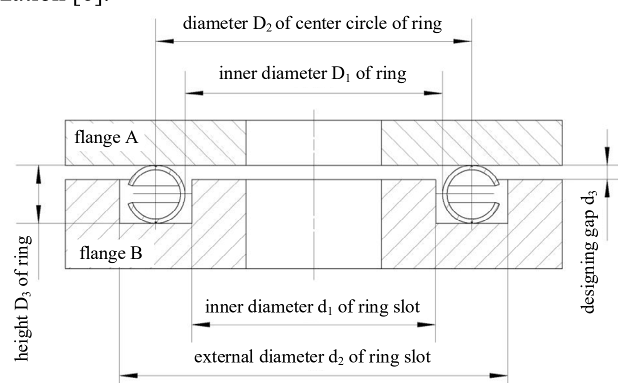

Figure 1: The force diagram of structure for c-section seals(a) and core dimensions of structure for c-section seals(b).

Helium Injection Leak Test and Result Analysis

Method for measuring the working performance of ultra-high vacuum metal sealing rings

In the accelerator ultra-high vacuum system, the plastic deformation during the sealing process is provided by the sealing ring, so the sealing ring is usually used once or several times. Therefore, the performance measurement objectives of ultra-high vacuum sealing ring tooling are the compression amount - line load, and line load - sealing leakage rate performance curves during one or several cycles of loading and unloading [7].

The comprehensive compression rebound test bench is commonly used to determine the compression amount linear load curve during the loading unloading cycle. At present, domestic manufacturers of comprehensive testing platforms include Ningbo Tiansheng Sealing Co., Ltd. and East China University of Science and Technology. Compress the sealing ring with a linear increase in load to obtain the loading curve between the compression amount and the line load, and then linearly reduce the load to obtain the unloading curve between the compression amount and the line load. During the loading unloading process, the sealing ring undergoes elastic stage, yield stage, strengthening

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-250-9 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2023-THPPP029

Content from this work may be used under the terms of the CC-BY-4.0 licence (© 2023). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

stage, and residual deformation stage during unloading [8]. Obtain the three important characteristic parameters of the maximum compression amount in the elastic stage, the line load of the maximum working compression amount, and the rebound amount after unloading from the curve, and be able to judge and predict the performance of the sealing ring in the special working environment.

The sealing structure composed of sealing rings, flanges, and flange chains is combined with a helium mass spectrometer leak detector to form a vacuum system, as shown in the schematic diagram in Figure 2. In the experiment, a comprehensive compression test bench can be used to apply dense sealing load, and in industrial practice, the working sealing pressure of the flange chain can be directly applied using a digital torque wrench [9]. During the loading unloading process of linear load variation, combined with the helium injection method to measure the sealing ring leakage rate value, the sealing ring linear load sealing leakage rate test curve is obtained, and the sealing performance data in operation is measured.

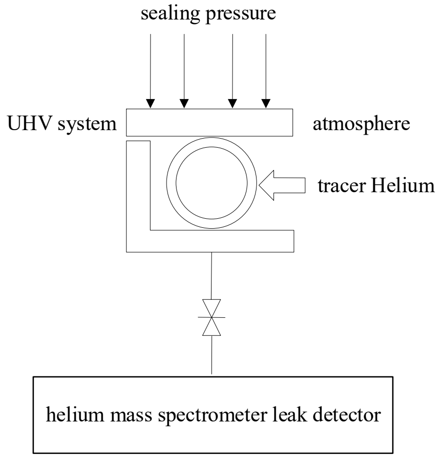

Figure 2: The sketch of testing the relationship curve of compress pressure leak rate.

REFERENCES

[1] Y. Liu *et al.*, “Failure Analysis on Rubber Sealing Structure of Mandrel Hanger and Improvement in Extreme Environment”, *Engineering Failure Analysis*, vol. 125, pp. 1844-2002, 2021.

[2] H. L. Zhao, “Metal Sealing Performance of Subsea X-tree Wellhead Connector Sealer”, *Chinese Journal of Mechanical Engineering*, vol. 28, pp. 649-656, 2015.

[3] X. J. Cui, R. Zhang, F. Han, *et al.*, “Finite element analysis and experimental research on metal to metal sealing components”, *Petroleum Machinery*, vol. 42, pp. 107-115, 2014.

[4] C. Hou, H. L. Qin, W. S. Xiao, *et al.*, “Sealing Mechanism and Performance Analysis of Circular Metal Sealing Assembly”, *Lubrication and Sealing*, vol. 39, pp. 34-39, 2014.

[5] W. C. Zhang, X. G. Li, S. J. Wei, *et al.*, “Simulation analysis and experimental verification of mechanical properties of metal O-rings”, *Lubrication and Sealing*, vol. 8, pp. 8-12, 2014.

[6] Y. Fang, “Research on unloading rebound characteristics and calculation methods”, *Journal of Water Resources and Building Engineering*, vol. 11, pp. 199-202, 2013.

[7] D. L. Zhu, S. X. Bai, “Experimental study on the rebound friction characteristics of fluororubber O-rings in reciprocating motion”, *Lubrication and Sealing*, vol. 43, pp. 67-75, 2018.

[8] W. W. Yu, L. X. Cai, Y. M. Ye, *et al.*, “Research on the rebound characteristics of Inconel718 alloy O-ring”, *Engineering Mechanics*, vol. 23, pp. 142-147, 2006.

[9] Q. D. Wang, X. B. Fang, L. J. Qian, *et al.*, “Design and Analysis of Automotive Leaf Springs Based on Virtual Prototyping Technology”, *Journal of Mechanical Engineering*, vol. 37, pp. 63-66, 2001.