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Domestic Application and Risk Management of Bimetallic Self-Sealing Composite Gasket in High Temperature Petrochemical Equipment

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Abstract: This paper addresses the stringent requirements for sealing technology in high-temperature and high-pressure petrochemical equipment, and introduces the key technologies and performance studies for the domestication of bimetallic self-sealing composite gaskets. The gasket features a composite structure of a double-layer metal framework and flexible graphite, relying on the "pressure self-sealing" mechanism to maintain excellent sealing performance even under high-temperature conditions. The article systematically elaborates on its material process innovations, thermomechanical coupling experiments, and methods for verifying sealing integrity, and establishes a life prediction and engineering risk management system, providing a technical route and theoretical support for the reliable application of high-end sealing components in the petrochemical field in China.

Keywords: Double-layer metal skeleton self-sealing gasket; High-temperature petrochemical equipment; Graphite composite layer

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1. Introduction

As the petrochemical industry evolves towards high-temperature and high-pressure conditions, the sealing performance of equipment faces increasingly severe challenges. The petrochemical industry policy released in 2023 explicitly lists enhancing the reliability of key equipment as a key development direction. High-temperature environments impose stringent requirements on sealing materials. For instance, they need to possess excellent thermal stability, creep resistance, and corrosion resistance. Traditional sealing materials often struggle to meet these comprehensive performance indicators. The self-sealing composite gasket based on a double-layer metal skeleton structure effectively addresses this challenge through innovative design. It utilizes a double-layer metal-formed skeleton to establish rigid contact with the flange, and simultaneously fills micro-gaps with surfacecompounded graphite material, achieving a durable and reliable seal under high-temperature conditions. From skeleton structure optimization, graphite compounding process, to performance verification system, relevant research provides a complete technical path for enhancing the performance of domestic seals, which is of great strategic significance for ensuring the safe operation of petrochemical equipment.

2. Technical basis of bimetallic self-sealing composite gasket

2.1. Analysis of demand for high-temperature petrochemical sealing technology

Under high-temperature and high-pressure conditions, petrochemical equipment has stringent requirements for sealing materials. In terms of thermal stability, due to the high operating temperature of the equipment, the sealing material must maintain stable performance at high temperatures to avoid structural damage or degradation of sealing performance caused by temperature changes [1]. Creep resistance is also crucial. When subjected to long-term pressure, the material should prevent slow deformation to ensure the durability of the sealing effect. Regarding corrosion resistance, the petrochemical environment is complex, with various corrosive media present. The sealing material must be able to resist corrosion and prevent leakage. Traditional sealing materials fall short in these aspects. Their failure mechanisms include structural changes in the material at high temperatures, creep due to inability to withstand long-term pressure, and susceptibility to corrosion, which cannot meet the sealing requirements of high-temperature petrochemical equipment.

2.2. Innovative features of bimetallic composite structure

The design of the double-layer metal skeleton structure is innovative. In principle, it adopts a double-layer skeleton design composed of the same metal material, ensuring structural consistency through precision molding processes. Simultaneously, it utilizes the synergistic effects of temperature rise, internal pressure, elastic deformation, and plastic deformation to achieve self-sealing functionality [2]. The surface composite graphite layer closely adheres to the flange metal surface. The high-temperature stability and flexibility of graphite material effectively fill micro-gaps, maintaining long-lasting sealing under high-temperature and high-pressure conditions. Elastic deformation allows the gasket to quickly adapt to the unevenness of the flange surface when pressed, forming an initial seal. Plastic deformation further strengthens the sealing interface through local material flow, ensuring stable sealing performance even under long-term thermal cycling or stress fluctuations. This “double-layer metal skeleton-graphite layer” composite structure is one of the key innovative features of the gasket in adapting to complex working conditions in high-temperature petrochemical equipment.

3. Path to breakthroughs in key localization technologies

3.1. Innovation in material composite manufacturing process

The precision forming process of the double-layer metal skeleton is a crucial step in the manufacturing process. During the forming process, it is necessary to strictly control parameters such as mold precision, rotational speed, and temperature to ensure the consistency of the skeleton structure and dimensional stability [3]. To address the issue of residual stress, by optimizing annealing process parameters, such as temperature curve, holding time, etc., and combining mechanical sizing technology, the internal stress generated during processing is effectively eliminated, avoiding deformation or performance degradation caused by stress concentration. At the same time, advanced online detection methods are used to monitor the quality of the formed skeleton, ensuring that its geometric accuracy and mechanical properties meet the stringent requirements of high-temperature petrochemical equipment. This precision forming process provides an important guarantee for the reliability and durability of the bimetallic self-sealing composite gasket.

3.2. Surface modification technology

Graphite composite layer coating technology is a key aspect of surface modification treatment. By optimizing coating process parameters, such as coating pressure, temperature profile, and curing time, this technology can significantly enhance the bonding strength between the graphite layer and the metal skeleton [4]. The use of precisely controlled coating equipment ensures that the graphite layer is uniformly and densely coated on the surface of the metal skeleton, forming a stable interfacial bond. This graphite-metal composite structure exhibits excellent adaptability under high-temperature conditions. The graphite layer not only effectively fills the micro-defects on the flange contact surface, but its unique thermal stability and self-lubricating properties also significantly reduce thermal stress concentration. By optimizing the formulation of graphite materials and coating processes, the sealing reliability and service life of composite gaskets in high-temperature and high-pressure environments can be further improved, meeting the stringent requirements of petrochemical equipment.

4. Experimental study on performance under high-temperature conditions

4.1. Thermal-mechanical coupling test

4.1.1. Thermal cycle load test

A thermal shock cycle experimental model was established to test the double-layer metal skeleton self-sealing composite gasket. This model simulates the actual thermal cycling conditions in high-temperature petrochemical equipment, focusing on investigating the performance evolution of the graphite layer under repeated thermal shocks. During the experiment, the stability of the graphite layer at high temperatures was evaluated by monitoring the compression-rebound performance of the gasket and the changes in sealing interface contact stress. Microstructural analysis showed that the graphite layer can effectively buffer the thermal stress between the metal skeleton and the flange during thermal cycling, and its unique layered structure helps maintain tight contact at the interface. This design significantly improves the sealing reliability of the gasket under severe temperature fluctuations, providing important performance data support for domestic applications [5].

4.1.2. Creep relaxation behavior test

The high-temperature creep characteristics of double-layer metal skeleton gaskets were studied using a stepwise loading method, with a focus on the regulating effect of the metal skeleton and graphite layer on stress relaxation behavior. The experimental system simulated the complex stress-temperature coupling conditions in petrochemical equipment, and stress decay curves at different temperatures were obtained through precise control of the loading process. The results showed that the plastic flow characteristics of the graphite layer could effectively compensate for the creep deformation of the metal skeleton, maintaining stable sealing contact pressure. The constitutive model established based on experimental data accurately described the mechanical response law of the graphite-metal composite structure at high temperatures, providing a theoretical basis for predicting the long-term service performance of the gasket [6].

4.2. Verification of sealing integrity

4.2.1. Helium mass spectrometer leak detection experiment

A novel combined sealing surface testing device was designed for assessing the sealing performance of double-layer metal-framed self-sealing gaskets under high-temperature conditions. The experiment utilized 99.9% high-purity nitrogen as the medium and combined it with helium mass spectrometer leak detection technology to precisely measure the leakage rate under varying compressive stress conditions. The relationship between leakage rate and sealing performance was systematically analyzed. During the experiment, key parameters such as temperature and pressure were strictly controlled to simulate the actual high-temperature and high-pressure conditions of petrochemical equipment. The focus was on investigating the behavior of the graphite layer under thermal cycling and creep conditions. It was found that the graphite layer could effectively fill micro-gaps at high temperatures, significantly enhancing the sealing effect. By recording the leakage rate data and corresponding changes in compressive stress, a relationship curve was plotted, providing a reliable basis for evaluating the sealing integrity of the gasket under high-temperature conditions. This research offers important technical support for the localization and engineering risk management of such gaskets [7].

4.2.2. Service life prediction model

A fatigue propagation rate calculation based on the Paris formula is used to construct a life assessment equation. By studying the material fatigue propagation behavior of double-layer metal skeleton self-sealing gaskets under high-temperature conditions, the Paris formula is accurately applied to calculate their fatigue propagation rate [8]. Considering the actual service conditions of the gaskets in petrochemical equipment, including the influence of temperature, pressure, medium, and other factors on material fatigue behavior, the formula is appropriately modified. The modified propagation rate is combined with parameters such as the initial defect size and critical defect size of the gasket to construct a service life prediction model. This model can accurately predict the service life of the gasket in high-temperature petrochemical equipment, providing an important basis for the safe operation and maintenance of the equipment.

5. Engineering application risk management system

5.1. Risk identification and assessment

5.1.1. Design and material risks

In the risk assessment of double-layer metal skeleton self-sealing composite gaskets, graphite layer aging and metal skeleton fatigue are the primary risk factors. Under high-temperature conditions, the graphite layer gradually undergoes oxidation and structural loosening, leading to a decline in its sealing performance. Simultaneously, the metal skeleton may develop fatigue cracks under long-term cyclic loading, affecting the overall structural integrity [9]. Therefore, it is necessary to establish a high-temperature aging evaluation system for graphite materials, quantifying the performance degradation patterns through accelerated aging experiments. For the metal skeleton, fatigue life testing should be conducted to analyze the characteristics of crack initiation and propagation. By constructing a multidimensional evaluation matrix encompassing material, structure, and operating conditions, the failure risk of the gasket under different service environments can be systematically assessed, providing a basis for optimal design.

5.1.2. Production and manufacturing risks

In the manufacturing process, it is crucial to utilize the FMEA (Failure Mode and Effects Analysis) method to analyze the impact of process parameter fluctuations on product quality. Fluctuations in process parameters may arise from various factors, such as equipment accuracy, differences in raw materials, and the skill level of operators. These fluctuations can lead to various failure modes in products, such as dimensional deviations and decreased sealing performance, which in turn affect product quality. Through the FMEA method, these potential failure modes can be systematically identified and their impact on product quality can be assessed. This helps manufacturers take proactive measures, such as optimizing process parameters, strengthening equipment maintenance, and personnel training, to reduce risks, ensure product quality meets requirements, and improve the application reliability of products in high-temperature petrochemical equipment [10].

5.2. Risk control measures

5.2.1. Potential directions for condition monitoring and intelligent early warning

For the application of bimetallic self-sealing composite gaskets in high-temperature petrochemical equipment, a local state monitoring method based on fiber Bragg grating sensing can be explored. This technology utilizes the sensitive characteristics of optical fibers to temperature and stress, embedding sensors at the gasket or key flange connections to collect temperature and stress data in real time, thus achieving indirect perception of the sealing state. Long-term data can be used to analyze the evolution trend of gasket performance and provide early warning signals in case of abnormal temperature rise or stress mutation, providing a basis for regular maintenance and risk prevention and control at key sealing points.

This type of monitoring method is particularly suitable for core sealing areas with high temperature, high pressure, or frequent process fluctuations. Through limited deployment, it can achieve state visualization of key areas. However, at present, this technology is still in the research and pilot application stage. For its actual promotion, comprehensive considerations must be made regarding cost, reliability, and compatibility with existing equipment management systems. In the future, with the reduction in the cost of sensing technology and the promotion of intelligent operation and maintenance modes, this type of localized and refined monitoring approach is expected to become a beneficial supplement to the management of key sealing points in petrochemical plants.

5.2.2. Standardized management process

In the domestic application of bimetallic self-sealing composite gaskets in high-temperature petrochemical equipment, it is necessary to establish QHSE management system documents covering the entire cycle of design, manufacturing, and installation. During the design phase, the gasket structure and materials must be precisely designed based on the specific parameters and operating conditions of the high-temperature petrochemical equipment to ensure its sealing performance and high-temperature resistance. The manufacturing process strictly controls the quality of raw materials and adopts advanced processes to ensure the dimensional accuracy and performance consistency of the gaskets. In the installation process, detailed operating procedures are formulated, and professional training is provided to installation personnel to ensure correct installation. At the same time, a quality supervision and inspection mechanism is established to strictly inspect products at each stage and rectify non-conformities in a timely manner. Attention should also be paid to environmental, health, and safety management to reduce environmental impact and ensure personnel health and safety.

5.3. Emergency management mechanism

5.3.1. Stability enhancement strategy based on self-sealing mechanism

Focusing on the special sealing mechanism of double-layer metal skeleton self-sealing composite gaskets under high-temperature conditions, the long-term sealing stability can be further enhanced by optimizing their structural design and material system. The unique “pressure self-sealing” characteristic of this gasket enables it to generate self-reinforced sealing stress under the action of medium pressure. This inherent advantage provides a solid foundation for sealing reliability under complex high-temperature conditions. By improving the material compatibility and structural morphology of the double-metal skeleton, its adaptive compensation ability under temperature fluctuations can be significantly enhanced. The performance durability of the graphite sealing layer has a decisive impact on the overall lifespan of the gasket.

Using specially treated flexible graphite materials and enhancing their anti-aging and anti-creep characteristics through optimized composite processes can effectively maintain a long-term stable sealing state. Multiple experiments have shown that the comprehensively optimized gasket can maintain excellent sealing performance even after multiple thermal cycles under high-temperature conditions. This technical approach focuses on improving the performance of the gasket itself by fully utilizing its self-sealing characteristics and optimizing the durability of key materials, significantly enhancing its reliability and service life under high-temperature and high-pressure environments. This deep optimization based on inherent mechanisms provides a more fundamental and easily scalable solution for high-temperature flange sealing, with good engineering application prospects.

5.3.2. Quick replacement and emergency response plan

For the domestic application of bimetallic self-sealing composite gaskets in high-temperature petrochemical equipment, it is crucial to establish an efficient rapid replacement and emergency response system. Since the gasket will leak once damaged and cannot be repaired online, it is necessary to focus on improving the spare parts management mechanism and optimizing the gasket replacement process. Standardized replacement procedures should be pre-designed for different models and equipment operating conditions, and specialized disassembly and assembly tools and positioning fixtures should be equipped to achieve rapid positioning and safe replacement of damaged gaskets.

At the same time, it is necessary to establish a comprehensive emergency response plan, clarifying the operational procedures, personnel division, and safety precautions in case of a leakage. This ensures that a professional team can be quickly organized for efficient handling in emergencies. Through systematic technical training and emergency drills, the proficiency of on-site personnel in gasket replacement operations and their ability to handle emergencies can be improved.

This system is dedicated to minimizing equipment downtime, controlling maintenance costs, and ensuring the safe and stable operation of high-temperature petrochemical equipment, providing reliable technical support for the large-scale industrial application of bimetallic self-sealing composite gaskets.

6. Conclusion

The domestic application of double-layer metal skeleton self-sealing composite gaskets in high-temperature petrochemical equipment has achieved remarkable results. The core technological breakthrough is mainly reflected in the innovative combination of the design of the same type of metal double-layer skeleton and high-performance graphite composite technology. By optimizing the structural precision of the metal skeleton and the graphite layer coating process, the sealing reliability issue under high-temperature conditions has been successfully addressed, and large-scale applications have been realized in multiple petrochemical projects. Currently, there are still challenges such as the need to improve simulation methods for extreme conditions and deepen digital management throughout the entire life cycle. It is suggested to establish a collaborative innovation platform for industry, academia, research, and application, focusing on tackling key technologies such as high-temperature modification of graphite materials and intelligent monitoring, while accelerating the development of a domestic sealing component standard system aligned with international standards. These measures will further enhance product quality and competitiveness, providing more reliable technical support for the safe operation of petrochemical equipment.

Disclosure statement

The author declares no conflict of interest.

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