What Is $MoSi_2$ Heating Element

中钨智造科技有限公司

CTIA GROUP LTD

CTIA GROUP LTD

Global Leader in Intelligent Manufacturing for Tungsten, Molybdenum, and Rare Earth Industries

电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

INTRODUCTION TO CTIA GROUP

CTIA GROUP LTD， a wholly-owned subsidiary with independent legal personality established by CHINATUNGSTEN ONLINE , is dedicated to promoting the intelligent, integrated, and flexible design and manufacturing of tungsten and molybdenum materials in the Industrial Internet era. CHINATUNGSTEN ONLINE, founded in 1997 with www.chinatungsten.com as its starting point—China's first top-tier tungsten products website—is the country's pioneering e-commerce company focusing on the tungsten, molybdenum, and rare earth industries. Leveraging nearly three decades of deep experience in the tungsten and molybdenum fields, CTIA GROUP inherits its parent company's exceptional design and manufacturing capabilities, superior services, and global business reputation, becoming a comprehensive application solution provider in the fields of tungsten chemicals, tungsten metals, cemented carbides, high-density alloys, molybdenum, and molybdenum alloys.

Over the past 30 years, CHINATUNGSTEN ONLINE has established more than 200 multilingual tungsten and molybdenum professional websites covering more than 20 languages, with over one million pages of news, prices, and market analysis related to tungsten, molybdenum, and rare earths. Since 2013, its WeChat official account "CHINATUNGSTEN ONLINE" has published over 40,000 pieces of information, serving nearly 100,000 followers and providing free information daily to hundreds of thousands of industry professionals worldwide. With cumulative visits to its website cluster and official account reaching billions of times, it has become a recognized global and authoritative information hub for the tungsten, molybdenum, and rare earth industries, providing 24/7 multilingual news, product performance, market prices, and market trend services.

Building on the technology and experience of CHINATUNGSTEN ONLINE, CTIA GROUP focuses on meeting the personalized needs of customers. Utilizing AI technology, it collaboratively designs and produces tungsten and molybdenum products with specific chemical compositions and physical properties (such as particle size, density, hardness, strength, dimensions, and tolerances) with customers. It offers full-process integrated services ranging from mold opening, trial production, to finishing, packaging, and logistics. Over the past 30 years, CHINATUNGSTEN ONLINE has provided R&D, design, and production services for over 500,000 types of tungsten and molybdenum products to more than 130,000 customers worldwide, laying the foundation for customized, flexible, and intelligent manufacturing. Relying on this foundation, CTIA GROUP further deepens the intelligent manufacturing and integrated innovation of tungsten and molybdenum materials in the Industrial Internet era.

Dr. Hanns and his team at CTIA GROUP, based on their more than 30 years of industry experience, have also written and publicly released knowledge, technology, tungsten price and market trend analysis related to tungsten, molybdenum, and rare earths, freely sharing it with the tungsten industry. Dr. Han, with over 30 years of experience since the 1990s in the e-commerce and international trade of tungsten and molybdenum products, as well as the design and manufacturing of cemented carbides and high-density alloys, is a renowned expert in tungsten and molybdenum products both domestically and internationally. Adhering to the principle of providing professional and high-quality information to the industry, CTIA GROUP's team continuously writes technical research papers, articles, and industry reports based on production practice and market customer needs, winning widespread praise in the industry. These achievements provide solid support for CTIA GROUP's technological innovation, product promotion, and industry exchanges, propelling it to become a leader in global tungsten and molybdenum product manufacturing and information services.

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sales@chinatungsten.com

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Chapter 1 Introduction

1.1 Overview of $MoSi_2$ Heating Elements

Molybdenum disilicide ($MoSi_2$) is an intermetallic compound with the chemical formula $MoSi_2$. It has a high melting point (about 2030°C), excellent high-temperature oxidation resistance, and good electrical and thermal conductivity. It is widely used in the field of high-temperature heating because it has the characteristics of both metal and ceramic. As a resistive heating material, molybdenum disilicide heating elements are mainly used in electric heating equipment under high-temperature oxidizing atmosphere. A dense silicon dioxide (SiO_2) protective film will be generated on its surface at high temperature, which effectively prevents further internal oxidation, thereby extending the service life. $MoSi_2$ heating elements can work stably in the temperature range of 500-1850°C, and are suitable for industrial and scientific research fields such as ceramic sintering, glass melting, metal heat treatment, high-temperature sintering, and laboratory high-temperature furnaces. Compared with other heating materials such as silicon carbide (SiC), molybdenum disilicide has a higher operating temperature and better high-temperature oxidation resistance, but its low-temperature brittleness and high-temperature creep performance limitations also limit some structural applications. Currently, $MoSi_2$ heating elements have various shapes, including U-shape, W-shape, L-shape and customized shapes, which can widely meet the needs of different industrial furnaces.

1.2 Development History of $MoSi_2$ Heating Elements

The study of molybdenum disilicide as a high-temperature material began in the early 20th century, but its application as a heating element began in the mid-20th century. In 1904, scientists first reported the crystal structure of $MoSi_2$ and confirmed that it was a tetragonal α-type crystal with a high melting point and the characteristics of an intermetallic compound. However, due to the limitations of preparation technology and material purity at the time, $MoSi_2$ was mainly used as a laboratory research object rather than an industrial material. In the 1930s, with the in-depth research on high-temperature alloys and ceramic materials, $MoSi_2$ began to attract attention due to its excellent high-temperature oxidation resistance and conductivity. Researchers found that the SiO_2 protective film formed on the surface of $MoSi_2$ in a high-temperature oxidizing atmosphere can significantly improve its durability, which laid a theoretical foundation for the subsequent development of heating elements.

In 1947, Kanthal of Sweden took the lead in producing the first industrialized molybdenum disilicide heating rod, marking the official entry of $MoSi_2$ heating elements into the commercial application stage. These early heating rods were mainly used in high-temperature industrial furnaces, with a maximum operating temperature of about 1600°C. Kanthal significantly improved the mechanical strength and oxidation resistance of the components by optimizing the sintering process and doping technology of $MoSi_2$. In the 1950s and 1960s, with the emergence of advanced preparation technologies such as vacuum sintering and plasma spraying, the production efficiency and performance of $MoSi_2$ heating elements were further improved. The shape of the element has evolved from a single straight rod to a U-type and an L-type to meet the needs of different furnace types. In addition, researchers have improved the brittleness of $MoSi_2$ at low temperatures and the creep properties at high temperatures by doping rare earth elements or other metals (such as W and Nb), further expanding its application range.

In the 1980s, China began to realize the industrial production of molybdenum disilicide heating elements. In the early stage, it mainly relied on imported technology, but gradually formed independent research and development capabilities. During this period, the maximum operating temperature of $MoSi_2$ heating elements has been increased to 1800°C, and they are widely used in industries such as ceramics, glass and refractory materials. During this period, Sweden's Kanthal company launched the Kanthal Super 1900 heating element, which has a maximum operating temperature of 1850°C and has become an industry benchmark. The success of this product is due to the use of high-purity raw materials and the improvement of cold-end and hot-end welding technology, which significantly enhances the stability of the element in high and low temperature cycles.

Since the 1990s, the research and development focus of $MoSi_2$ heating elements has shifted to performance optimization and application expansion. New preparation processes such as hot pressing sintering, reaction sintering and self-propagating high temperature synthesis (SHS) have significantly improved the density and mechanical properties of the material. At the same time, the development of $MoSi_2$ coating technology has enabled it to be used as a high-temperature protective coating in the aerospace field, such as for gas turbine blades and jet engine components. In addition, the development of nano-scale $MoSi_2$ powders has made it possible to prepare high-performance composite materials, partially solving the problem of its low-temperature brittleness. In terms of the global market, the $MoSi_2$ heating element market value was approximately US$103 million in 2016 and is expected to reach US$135 million in 2022, with a compound annual growth rate of 4.7%, reflecting its continued demand in the high-temperature industrial field.

Although $MoSi_2$ heating elements perform well in high-temperature fields, their development still faces challenges. Low-temperature brittleness and insufficient high-temperature creep properties limit their application as structural materials, while high production costs also affect their competitiveness in the low-end market. In the future, research directions may focus on composite material development, doping modification, and new preparation processes to further improve performance and reduce costs.

1.3 Application status of molybdenum disilicide heating elements

Molybdenum disilicide ($MoSi_2$) heating elements play an important role in the global high-temperature industry due to their excellent high-temperature oxidation resistance, operating temperature up to 1850°C, and stable electrical properties. This element is widely used in high-temperature electric furnaces in industrial production, scientific research, and special material processing. Its core advantage is that it can operate stably for a long time in an oxidizing atmosphere, and the dense silicon dioxide (SiO_2) protective film generated on the surface effectively prevents internal oxidation, thereby significantly extending its service life. In recent years, advances in materials science and manufacturing processes have promoted the performance improvement of $MoSi_2$ heating elements. For example, through doping modification and advanced sintering technology, the low-temperature brittleness and high-temperature creep properties of the element have been improved, enabling it to adapt to more demanding working environments.

In the global market, the demand for $MoSi_2$ heating elements continues to grow, especially in the ceramic, glass and semiconductor industries. Sweden's Kanthal company dominates the market with its Kanthal Super series of products (such as Kanthal Super 1900), which are known for their excellent high-temperature performance and reliability. Enterprises in China, Japan and the United States are also actively developing and producing $MoSi_2$ heating elements, among which China has significant advantages in cost control and large-scale production. In terms of manufacturing process, technologies such as hot pressing sintering, reaction sintering and self-propagating high-temperature synthesis (SHS) have improved the density and mechanical properties of the material, and the shape of the element has also developed from a single straight rod to U-shaped, W-shaped, L-shaped and customized shapes to meet the needs of different furnace designs. In addition, the development of nano-scale $MoSi_2$ powders has opened up new application areas for high-performance composite materials and coatings, such as high-temperature protective coatings in the aerospace and energy industries.

Although $MoSi_2$ heating elements perform well in high-temperature fields, they still face some challenges. Low-temperature brittleness limits its potential in certain structural applications, while high production costs make it face competition from alternative materials such as silicon carbide (SiC) in the low-end market. Current research focuses include improving mechanical properties by doping rare earth elements or metals (such as W, Nb), and developing new composite materials to improve thermal shock resistance and durability. With the rise of intelligent high-temperature furnaces, the requirements for precise temperature control and long life of $MoSi_2$ heating elements have been further improved, which has promoted the development of related control technologies and material optimization. In the future, as the global demand for efficient, energy-saving and environmentally friendly production methods increases, $MoSi_2$ heating elements are expected to be used in more emerging fields.

1.4 Application industries of $MoSi_2$ heating elements

Molybdenum disilicide heating elements are widely used in many industries due to their high temperature stability, oxidation resistance and excellent electrical properties. The following are the main application areas: In the ceramic industry, $MoSi_2$ heating elements are key components in the sintering and high temperature processing processes for the production of structural ceramics, functional ceramics and refractory materials. Its maximum operating temperature of 1850°C can meet the sintering requirements of high-performance ceramics such as alumina, zirconia and silicon nitride, ensuring product quality and process stability. In the glass industry, $MoSi_2$ heating elements are widely used in high-temperature furnaces and annealing furnaces for the production of optical glass, flat glass and special glass. Its oxidation resistance and long life characteristics enable it to work continuously in a high-temperature oxidizing atmosphere, significantly improving production efficiency.

In the field of metal heat treatment, $MoSi_2$ heating elements are used in high temperature annealing, quenching and brazing processes, especially for the treatment of stainless steel, titanium alloys and high temperature alloys. Its rapid heating and precise temperature control capabilities improve product quality and process efficiency. In the semiconductor industry, high-temperature diffusion furnaces and oxidation furnaces often use $MoSi_2$ heating elements for silicon wafer heat treatment and thin film deposition processes. Its high purity and stability meet the semiconductor industry's stringent requirements for clean environment and precise temperature control.

In the aerospace field, $MoSi_2$ is not only used as a heating element, but also in the form of a coating for protective coatings on gas turbine blades and jet engine components. Its high-temperature oxidation resistance and corrosion resistance enable it to perform well in extreme environments. In the field of scientific research, $MoSi_2$ heating elements are widely used in high-temperature experimental furnaces in materials science, physics and chemistry laboratories, such as thermogravimetric analyzers, differential scanning calorimeters and high-temperature synthesis equipment, to provide support for the development of new materials. Refractory and metallurgical industries, $MoSi_2$ heating elements are used for high temperature treatment in refractory sintering and metallurgical processes, such as the production of high purity metals and alloys, and their high efficiency and long life reduce production costs.

In the field of energy and environmental protection, $MoSi_2$ heating elements are used in high-temperature incinerators, solid oxide fuel cell (SOFC) test equipment and waste thermal treatment systems, helping to achieve clean production and efficient energy utilization. $MoSi_2$ heating elements benefits from the advancement of its material properties and manufacturing technology. Different industries have different performance requirements. For example, the ceramic and glass industries pay more attention to high temperature stability and life, while the semiconductor industry emphasizes high purity and temperature control accuracy. In the future, as various industries have higher requirements for the performance of high-temperature equipment, $MoSi_2$ heating elements are expected to achieve breakthroughs in more fields through material optimization and process innovation.

CTIA GROUP LTD Silicon Molybdenum Rod

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$MoSi_2$ Heating Element Introduction

1. Overview of $MoSi_2$ Heating Element

Molybdenum disilicide ($MoSi_2$) heating elements are high-performance ceramic electric heating materials widely used in industrial furnace applications. In high-temperature oxidizing atmospheres, $MoSi_2$ forms a dense silica (SiO_2) protective layer on its surface, which effectively prevents further oxidation. It exhibits excellent oxidation resistance and thermal stability, allowing stable operation under high temperatures for extended periods.

2. Features of $MoSi_2$ Heating Element

Low thermal expansion coefficient: Well-matched with common ceramic substrates, minimizing the risk of cracking caused by thermal stress.

Excellent oxidation resistance: Forms a dense SiO_2 protective film on the surface, effectively preventing material degradation from oxidation.

Extremely high working temperature: Capable of continuous operation up to 1700°C, and a maximum usage temperature of 1800°C in oxidizing atmospheres.

Good high-temperature electrical resistance characteristics: $MoSi_2$ exhibits relatively stable resistivity at high temperatures, with only a gradual increase in resistivity at elevated temperatures.

3. Specifications of $MoSi_2$ Heating Element

Model (d1/d2)	Hot End Diameter (d1)	Cold End Diameter (d2)	Hot Zone Length (Le)	Cold Zone Length (Lu)	Common Types
φ3/6	3 mm	6 mm	100–300 mm	150–250 mm	Straight / U-type
φ4/9	4 mm	9 mm	100–500 mm	200–300 mm	Straight / U-type
φ6/12	6 mm	12 mm	100–600 mm	200–350 mm	Straight / U-type / W-type
φ9/18	9 mm	18 mm	150–800 mm	250–400 mm	Straight / U-type / W-type
φ12/24	12 mm	24 mm	200–1000 mm	300–500 mm	Straight / U-type / W-type

4. Typical Applications of $MoSi_2$ Heating Element

High-temperature sintering furnaces in the ceramics and powder metallurgy industries

Heat treatment equipment for steel and non-ferrous metals

High-temperature laboratory furnaces

Diffusion, annealing, and oxidation processes in the semiconductor and photovoltaic industries

5. Purchasing Information

Email: sales@chinatungsten.com; Phone: +86 592 5129595; 592 5129696

Website: www.molybdenum.com.cn

Chapter 2 Characteristics of $MoSi_2$ Heating Elements and Their Influencing Factors

2.1 Physical properties of $MoSi_2$ heating elements

Molybdenum disilicide ($MoSi_2$) is an intermetallic compound that combines the characteristics of metals and ceramics. Its physical properties determine its excellent performance as a high-temperature heating element. The crystal structure of $MoSi_2$ is tetragonal α-type (C11b-type) with a space group of I4/mmm, which has high symmetry and stability. Its melting point is about 2030℃, which enables it to maintain structural integrity at extremely high temperatures. The density is 6.24 g/cm³, which is relatively low, which helps to reduce the weight of the heating element and is suitable for complex shape design. The thermal expansion coefficient of $MoSi_2$ is about 8.1×10^{-6} K^{-1} (room temperature to 1000℃), which matches well with common ceramic matrix materials (such as alumina and zirconia), reducing the risk of cracking caused by thermal stress.

$MoSi_2$ is about 45 W/(m·K) at room temperature, and gradually decreases with increasing temperature, but it can still effectively transfer heat at high temperatures to ensure uniform heating of the heating element. It has a high hardness, with a Vickers hardness of about 1200 HV, and has good wear resistance, but its brittleness at low temperatures (fracture toughness of about 2-3 MPa·$m^{1/2}$) makes it susceptible to mechanical impact damage. $MoSi_2$'s oxidation resistance is particularly outstanding in high-temperature oxidizing atmospheres. A dense SiO_2 protective film will be generated on the surface above 800°C, effectively preventing further diffusion of oxygen and protecting the internal structure from oxidation erosion. This feature enables it to work for a long time in an oxidizing atmosphere, with a maximum operating temperature of up to 1850°C.

$MoSi_2$ are affected by many factors. The purity of the raw materials is the key. High-purity $MoSi_2$ can reduce the grain boundary weakening caused by impurities and improve the mechanical properties and oxidation resistance. Preparation processes such as hot pressing sintering or reaction sintering will affect the density of the material. The higher the density, the better the oxidation resistance and thermal conductivity. Doping modification (such as adding Al, W or rare earth elements) can improve its low-temperature brittleness and high-temperature creep properties, but may slightly reduce oxidation resistance. In addition, the working environment (such as atmosphere type and temperature cycle frequency) also has a significant effect on the stability of physical properties. For example, in a reducing atmosphere, the SiO_2 protective film may fail, resulting in accelerated degradation of the material.

2.2 Resistivity of $MoSi_2$ Heating Elements

The resistivity of $MoSi_2$ heating elements is the core performance parameter of $MoSi_2$ as an electric heating material, which directly affects the heating efficiency and temperature control accuracy. The resistivity of $MoSi_2$ shows nonlinear characteristics with temperature changes. At room temperature, its resistivity is about 2.0×10^{-5} Ω· cm. As the temperature rises, the resistivity gradually increases, reaching about 4.0×10^{-5} at around 1000℃. Ω· cm. This positive temperature coefficient characteristic enables the $MoSi_2$ heating element to automatically adjust power at high temperatures, prevent overheating, and improve safety. Above 1000°C, the resistivity increases slowly and becomes stable, which helps to accurately control the temperature in the high temperature range.

$MoSi_2$ is affected by the material composition, microstructure and external environment. The purity and impurity content of the raw materials have a significant effect on the resistivity. For example, impurities such as iron and aluminum will increase the resistivity and reduce stability, while high-purity $MoSi_2$ exhibits more consistent electrical properties. Grain size and grain boundary characteristics are also crucial. Smaller grain sizes are usually accompanied by higher grain boundary resistance, resulting in slightly higher resistivity, but improved mechanical strength. The effect of the preparation process on the resistivity is also significant. $MoSi_2$ prepared by hot pressing sintering has a higher density, fewer grain boundary defects, and a lower and stable resistivity, while reaction sintered samples may have a higher resistivity due to higher porosity.

Doping modification is an important means to adjust the resistivity of $MoSi_2$. Adding tungsten (W) or niobium (Nb) can reduce resistivity and enhance high-temperature conductivity, but may sacrifice some anti-oxidation properties. Rare earth element doping (such as Y_2O_3) stabilizes the change of resistivity with temperature by improving the grain boundary structure . The influence of the working environment on the resistivity cannot be ignored. In an oxidizing atmosphere, the formation of SiO_2 protective film has little effect on the resistivity, but in a reducing or vacuum environment, Si volatilization may occur on the surface, causing the resistivity to gradually increase, affecting the long-term stability.

$MoSi_2$ heating elements needs to be optimized according to specific applications. For example, ceramic sintering furnaces require stable resistivity to ensure uniform heating, while semiconductor heat treatment furnaces require lower resistivity for rapid temperature rise. In practical applications, the resistivity matching design of the cold end (usually doped with a more conductive material) and the hot end can improve overall efficiency and reduce energy loss.

2.3 High temperature resistance characteristics of $MoSi_2$ heating elements

Molybdenum disilicide ($MoSi_2$) heating elements is one of the core properties of electric heating materials, which directly affects its heating efficiency, temperature control accuracy and service life. In the high temperature range, the resistivity of $MoSi_2$ shows relative stability. Compared with the rapid increase from room temperature to 1000°C, the increase in resistivity in the high temperature section slows down significantly. For example, at room temperature, the resistivity of $MoSi_2$ is about 2.0×10^{-5} Ω· cm, and increases to about 4.0×10^{-5} at 1000°C Ω· cm, while at 1500°C it is about 4.5×10^{-5} Ω· cm, and then changes less as the temperature further increases. This positive temperature coefficient (PTC) property enables $MoSi_2$ to automatically adjust power output at high temperatures, avoid overheating, and improve safety. At the same time, it provides stable performance for applications that require precise temperature control, such as ceramic sintering and semiconductor heat treatment. The stability of high-temperature resistance characteristics stems from the intermetallic compound structure of $MoSi_2$, whose conductive mechanism is mainly based on metallic bonds. Even at high temperatures, the enhanced lattice vibration leads to increased electron scattering, and the conductivity remains at a high level.

However, long-term high-temperature operation may cause a slight drift in resistivity, which is mainly caused by composition changes caused by the growth of the surface SiO_2 protective film or trace Si volatilization, as well as microstructural evolution induced by thermal stress (such as grain growth or grain boundary weakening).

Factors affecting high-temperature resistance properties include material purity, doping modification, and working environment. High-purity $MoSi_2$ can reduce resistance instability caused by impurities (such as Fe and Al) and ensure consistency of electrical performance. Doping with metal elements (such as W and Nb) can reduce resistivity and enhance high-temperature conductivity, but may slightly reduce oxidation resistance, while rare earth element doping (such as Y_2O_3) stabilizes the change of resistivity with temperature by optimizing the grain boundary structure. In an oxidizing atmosphere, the SiO_2 protective film has little effect on resistivity, but in a reducing or vacuum environment, Si volatilization will cause the resistivity to gradually increase and accelerate component aging. The preparation process also has an important influence on the resistance characteristics. $MoSi_2$ prepared by hot pressing sintering has high density, fewer grain boundary defects, and more stable resistance characteristics, while reaction sintered samples with higher porosity may have performance degradation due to local current unevenness. In practical applications, the cold end is usually doped with highly conductive materials to reduce resistance, and optimizing the resistance matching between the cold end and the hot end can improve energy efficiency. Regular maintenance and avoiding extreme temperature cycling can help maintain the long-term stability of high temperature resistor characteristics.

2.4 High temperature oxidation resistance of $MoSi_2$ heating elements

The high-temperature oxidation resistance of molybdenum disilicide heating elements is the key feature for long-term stable operation in an oxidizing atmosphere, making it the preferred material for high-temperature electric furnaces. Above 800°C, a dense silicon dioxide (SiO_2) protective film will quickly form on the surface of $MoSi_2$. This film has a low oxygen diffusion coefficient and good self-repairing ability, effectively preventing oxygen from penetrating into the interior and protecting the substrate from oxidation corrosion. Its oxidation reaction is: $2MoSi_2 + 7O_2 \rightarrow 2MoO_3 + 4SiO_2$, where MoO_3 volatilizes at high temperatures and the remaining SiO_2 forms a continuous protective layer. In the range of 1200-1850°C, this protective film enables $MoSi_2$ to operate stably for a long time in an oxidizing atmosphere, making it suitable for high-temperature processes such as ceramic sintering and glass melting. However, in the low-temperature range of 400-700°C, $MoSi_2$ is prone to "pesting", oxidizing to form a non-protective mixture of MoO_3 and SiO_2 , resulting in material pulverization, especially in frequent temperature cycles. To avoid this problem, this temperature range is usually passed quickly in practical applications . $MoSi_2$ has poor oxidation resistance in a reducing atmosphere (such as H_2) or a vacuum environment, because the SiO_2 protective film cannot be formed or is destroyed, resulting in Si volatilization and material degradation, so it is not suitable for such environments. Factors affecting high-temperature oxidation resistance include material purity, microstructure, and doping modification. High-purity $MoSi_2$ can reduce grain boundary oxidation caused by impurities and enhance the density of SiO_2 films . Dense microstructures (such as those obtained by hot pressing and sintering) can reduce oxygen diffusion paths and improve oxidation resistance. Doping with rare earth elements (such as Y_2O_3) or oxides can improve the adhesion and self-healing ability of SiO_2 films , while some metal doping (such as W) may reduce oxidation resistance by changing oxidation kinetics. The humidity of the working environment can also affect the oxidation resistance. In a high-humidity environment, SiO_2 films may undergo hydration reactions, reducing the protective effect. In order to improve high - temperature oxidation resistance, modern $MoSi_2$ heating elements often use surface coating technology (such as Al_2O_3 or ZrO_2 coatings) to enhance the protective effect, or improve the material density by optimizing the sintering process. In practical applications, maintaining a stable oxidizing atmosphere and avoiding frequent low-temperature cycles are the key to extending the antioxidant life.

2.5 Thermal conductivity and thermal diffusivity of $MoSi_2$ heating elements

The thermal conductivity and thermal diffusivity of $MoSi_2$ heating elements are important indicators of their thermal conductivity, which directly affect the heating rate, temperature uniformity and energy efficiency. The thermal conductivity of $MoSi_2$ is about 45 W/(m·K) at room temperature, and gradually decreases with increasing temperature to about 25 W/(m·K) at 1000°C, and further drops to about 15 W/(m·K) at 1500°C. Although the thermal conductivity decreases at high temperatures, $MoSi_2$ can still effectively transfer heat and ensure uniform temperature distribution in the furnace, which is suitable for applications such as ceramic sintering and glass melting that require high thermal uniformity.

The change in thermal conductivity is mainly due to the lattice vibration and electronic thermal conductivity mechanism of $MoSi_2$. At low temperatures, electronic thermal conductivity is dominant, while at high temperatures, enhanced phonon scattering causes a decrease in thermal conductivity. The thermal diffusivity of $MoSi_2$ ($\alpha = k / (\rho \cdot c)$, where k is thermal conductivity, ρ is density, and c is specific heat capacity) also changes with temperature.

At room temperature, the specific heat capacity of $MoSi_2$ is about 0.45 J/(g·K), the density is 6.24 g/cm³, and the thermal diffusion coefficient is about 1.6×10^{-5} m ² /s; at high temperatures, the specific heat capacity increases slightly, and the thermal diffusion coefficient decreases due to the decrease in thermal conductivity. Factors affecting thermal conductivity and thermal diffusion coefficient include material purity, microstructure, and doping modification. Impurities (such as Fe and C) increase phonon scattering and reduce thermal conductivity, while high-purity $MoSi_2$ has higher thermal conductivity. $MoSi_2$ with high density (such as hot-pressed sintered samples) has higher thermal conductivity, while samples with high porosity have lower thermal conductivity due to heat scattering from the pores.

The effect of doping modification is complex. Adding W can slightly increase thermal conductivity, while rare earth oxide doping may reduce thermal conductivity due to grain boundary scattering. In practical applications, thermal conductivity and thermal diffusivity need to be optimized according to the furnace type and process. For example, semiconductor heat treatment furnaces require higher thermal conductivity to achieve rapid heating, while large ceramic sintering furnaces pay more attention to thermal uniformity. Optimizing the preparation process (such as increasing density) and rationally designing the shape of components (such as increasing the hot end surface area) can improve thermal conductivity and reduce energy loss.

2.6 Thermal shock stability of $MoSi_2$ heating elements

Molybdenum disilicide ($MoSi_2$) heating elements refers to their ability to resist cracking or fracture induced by thermal stress under rapid temperature changes, and is an important indicator for evaluating their reliability in high-temperature cycling environments. The thermal shock stability of $MoSi_2$ is closely related to its low thermal expansion coefficient and moderate thermal conductivity. These characteristics enable $MoSi_2$ to better disperse thermal stress during rapid heating and cooling, and reduce internal stress concentration caused by temperature gradients. However, the low-temperature brittleness of $MoSi_2$ may still cause microcracks or fractures under severe thermal shock conditions, especially in frequent high and low temperature cycles. The performance of thermal shock stability directly affects the life and reliability of $MoSi_2$ heating elements in applications such as ceramic sintering furnaces and glass melting furnaces that require rapid heating or cooling. The main factors affecting thermal shock stability include material purity, microstructure and preparation process. High-purity $MoSi_2$ can reduce grain boundary weakening caused by impurities (such as Fe and Al), thereby reducing the risk of crack propagation induced by thermal shock. In terms of microstructure, dense $MoSi_2$ (such as prepared by hot pressing and sintering) has fewer pores and defects and can effectively disperse thermal stress, while samples with higher porosity are prone to local stress concentration under thermal shock, leading to cracking. Doping modification also has a significant effect on thermal shock stability. For example, the addition of rare earth oxides (such as Y_2O_3) or aluminum oxide (Al_2O_3) can increase grain boundary strength and enhance thermal shock resistance, while some metal doping (such as W) may slightly reduce thermal shock stability due to changes in thermal expansion characteristics. The temperature change rate and cycle frequency in the working environment are key external factors. Rapid thermal shock cycles (such as a sudden drop from 1500°C to room temperature) will aggravate thermal stress accumulation and shorten component life. In practical applications, optimizing the temperature control strategy in the furnace (such as slow temperature rise and fall) and designing a reasonable component shape (such as avoiding sharp edges to reduce stress concentration) can significantly improve thermal shock stability. In addition, surface coating technology (such as SiC or Al_2O_3 coating) can further improve the thermal shock resistance of $MoSi_2$ and extend its service life .

2.7 Thermal shock stability of $MoSi_2$ heating elements

The thermal shock stability of $MoSi_2$ heating elements refers to their ability to resist cracking or performance degradation under extreme temperature gradients or instantaneous thermal shocks (such as direct exposure to cold air or liquid cooling). It is closely related to thermal shock stability but emphasizes instantaneous and drastic temperature changes. The thermal shock stability of $MoSi_2$ benefits from its low coefficient of thermal expansion and moderate thermal conductivity, which together enable the material to better disperse thermal stresses in instantaneous temperature changes. However, due to the low fracture toughness of $MoSi_2$, it may experience microcrack propagation or even macroscopic fracture under severe thermal shock conditions, especially in the "plague" temperature range of 400-700°C, where thermal shock may aggravate oxidation and powdering, leading to material failure. Thermal shock stability is critical for the application of $MoSi_2$ heating elements in high-temperature furnaces with rapid start-up and shutdown or in non-uniform heating environments, such as in glass forming or metal heat

电话/TEL：0086 592 512 9696
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sales@chinatungsten.com

treatment processes. Factors affecting thermal shock stability include material composition, microstructure, and external environment.

$MoSi_2$ with higher purity can reduce stress concentration caused by impurities at grain boundaries and improve thermal shock resistance. A dense microstructure (such as that obtained by hot pressing or reaction sintering) can effectively reduce crack propagation induced by thermal shock, while samples with higher porosity have poor thermal shock stability due to more defects. Doping modification has a dual effect on thermal shock stability. For example, the addition of rare earth elements (such as La_2O_3) can enhance grain boundary bonding and improve crack resistance, while some metal doping may reduce stability due to thermal expansion mismatch. The thermal shock intensity (such as cold air injection or liquid cooling) and the number of cycles in the working environment can significantly affect the performance. Severe thermal shock can cause cracking of the surface SiO_2 protective film and reduce oxidation resistance. In practical applications, optimizing component design (such as using U-shaped or W-shaped structures to increase thermal stress dispersion) and controlling thermal shock conditions (such as avoiding direct exposure to cold media) can improve thermal shock stability. In addition, surface modification technologies (such as coating with high-toughness ceramic coatings) can enhance the thermal shock resistance of $MoSi_2$ and reduce crack propagation .

2.8 Thermal fatigue performance of $MoSi_2$ heating elements

The thermal fatigue performance of $MoSi_2$ heating elements refers to their ability to resist performance degradation (such as increased resistivity, decreased mechanical strength, or degradation of surface protective film) under repeated high-temperature-low-temperature cycles, and is a key indicator for evaluating their long-term reliability. The thermal fatigue performance of $MoSi_2$ is jointly affected by its low thermal expansion coefficient, moderate thermal conductivity, and high-temperature oxidation resistance. In an oxidizing atmosphere, the SiO_2 protective film formed on the surface of $MoSi_2$ can remain stable during multiple thermal cycles and slow down material degradation. However, during the thermal fatigue process, repeated thermal and mechanical stresses may cause the initiation and expansion of microcracks, especially in $MoSi_2$ with significant low-temperature brittleness , where thermal fatigue may cause component fracture or electrical performance drift. In addition, in the "plague" temperature range of 400-700°C, thermal fatigue cycles may aggravate oxidation pulverization and accelerate material failure. Thermal fatigue performance directly affects the life of $MoSi_2$ heating elements in applications such as ceramic sintering and metal heat treatment that require frequent thermal cycles. Factors affecting thermal fatigue performance include material purity, microstructure, doping modification and working environment.

High-purity $MoSi_2$ can reduce the weakening of grain boundaries caused by impurities and reduce the risk of thermal fatigue cracks. Dense microstructures (such as hot-pressed sintered samples) can effectively disperse cyclic thermal stress and improve thermal fatigue life, while samples with higher porosity are prone to failure due to stress concentration. Doping modification has an important influence on thermal fatigue performance. For example, the addition of rare earth oxides (such as Y_2O_3) or alumina can enhance grain boundary strength and inhibit crack propagation, while some metal doping may reduce thermal fatigue performance due to thermal expansion mismatch. The thermal cycle amplitude, frequency and atmosphere type in the working environment have a significant impact on thermal fatigue performance. For example, in a reducing or vacuum environment, the failure of the SiO_2 protective film will cause Si volatilization and accelerate thermal fatigue degradation. In practical applications, optimizing thermal cycle parameters (such as reducing the heating and cooling rate), improving component design (such as increasing the hot end strength) and using surface coating technology (such as SiC or ZrO_2 coating) can significantly improve thermal fatigue performance. Regular inspection and maintenance can also effectively extend the thermal fatigue life of $MoSi_2$ heating elements.

2.9 Surface state of $MoSi_2$ heating element

Molybdenum disilicide ($MoSi_2$) heating elements has an important influence on their high temperature performance, service life and reliability. The surface characteristics of $MoSi_2$ are mainly reflected in its naturally formed SiO_2 oxide film, surface microstructure and the performance of the applied protective coating. In a high temperature oxidizing atmosphere, a dense SiO_2 protective film will be generated on the surface of $MoSi_2$ above 800°C . This film is the key to its excellent oxidation resistance, which can effectively prevent oxygen from diffusing inward and protect the substrate from oxidation corrosion. However, the surface state is not only affected by the oxide film, but also closely related to surface defects (such as microcracks, pores), coating quality and surface evolution during long-term use. The surface state of $MoSi_2$ directly determines its stability under high temperature cycles, thermal shock and thermal fatigue conditions, especially in high-demand applications such as ceramic sintering, glass melting and semiconductor heat treatment.

The quality of the surface state is affected by many factors, including material purity, preparation process and working environment. High-purity $MoSi_2$ can reduce the weakening of grain boundaries caused by surface impurities (such as Fe, Al) and generate a more uniform and dense SiO_2 film . Preparation processes such as hot pressing sintering or reaction sintering have a significant effect on surface roughness and porosity. The surface of $MoSi_2$ prepared by hot pressing sintering is smoother and has fewer defects, which is conducive to the formation of a stable oxide film, while the reaction sintered samples may reduce the protective effect due to more surface pores. The atmosphere type, humidity and temperature cycle frequency in the working environment will also affect the surface state. For example, a high humidity environment may cause the SiO_2 film to hydrate and reduce its protective ability, while frequent temperature cycles may cause surface cracks or coating peeling. In order to optimize the surface state, modern $MoSi_2$ heating elements often improve oxidation resistance and durability through surface modification (such as coating technology) or process optimization (such as surface polishing).

The long-term stability of the surface state is crucial to the performance of $MoSi_2$ heating elements. During long-term operation at high temperatures, the surface SiO_2 film may become thinner due to Si volatilization or MoO_3 volatilization, especially in a reducing or vacuum environment, and the surface protection ability will be significantly reduced. In addition, the initiation and propagation of surface microcracks may be aggravated by thermal stress or mechanical stress, especially under thermal shock or thermal fatigue conditions. In practical applications, regular inspection of the surface state, optimization of the heating and cooling rates, and the use of protective coatings are effective measures to maintain the surface performance of $MoSi_2$ heating elements. In the future, with the development of surface engineering technology, the optimization of the surface state of $MoSi_2$ will become an important direction to improve its comprehensive performance.

2.9.1 Commonly used protective coating types

To further enhance the oxidation resistance, thermal shock stability and thermal fatigue performance of molybdenum disilicide heating elements, surface coating technology is widely used in $MoSi_2$ elements. Common types of protective coatings include oxide coatings, carbide coatings and composite coatings, each of which targets specific performance requirements and application environments. Oxide coatings are the most common choice, among which aluminum oxide (Al_2O_3) and zirconium oxide (ZrO_2) coatings are favored due to their high melting point, chemical stability and low oxygen diffusion coefficient. Al_2O_3 coatings are applied by plasma spraying or chemical vapor deposition (CVD) to form a dense protective layer at high temperatures, significantly improving the oxidation resistance and thermal shock resistance of $MoSi_2$, especially for oxidizing atmospheres of 1500-1800°C.

ZrO_2 coatings are often used in applications requiring high thermal shock stability, such as high-temperature aerospace components, due to their excellent thermal barrier properties. Carbide coatings are mainly silicon carbide (SiC), because their thermal expansion coefficients match well with those of the $MoSi_2$ substrate , which can reduce thermal stress between the coating and the substrate and reduce the risk of spalling . SiC coatings are applied through plasma spraying or reaction sintering processes, which not only enhance oxidation resistance, but also improve the surface wear resistance, making them suitable for use in high-wear environments such as ceramic sintering furnaces. Composite coatings have been the focus of development in recent years, such as Al_2O_3 - SiC or ZrO_2-Y_2O_3 composite coatings, which combine the advantages of multiple materials to provide more comprehensive protection. For example, Al_2O_3 - SiC composite coatings combine the high oxidation resistance of Al_2O_3 and the thermal shock resistance of SiC, making them suitable for $MoSi_2$ components under complex working conditions .

The choice of coating type needs to be optimized according to the specific application environment. For example, semiconductor heat treatment furnaces require high purity coatings to avoid contamination, while glass melting furnaces pay more attention to the coating's thermal shock resistance and corrosion resistance. The preparation process of the coating also has a significant impact on the performance.

Plasma spraying can form thick and dense coatings, which are suitable for industrial-scale applications, while the CVD process can produce more uniform and thin coatings with higher adhesion, which are suitable for high-precision requirements. In addition, the thickness and uniformity of the coating need to be precisely controlled.

A coating that is too thick may crack due to thermal stress mismatch, and a coating that is too thin may not provide adequate protection. In the future, the development of nanostructured coatings and multilayer composite coatings is expected to further improve the surface performance of $MoSi_2$ heating elements.

2.9.2 Study on surface cracks and coating adhesion

Surface cracks and coating adhesion of $MoSi_2$ heating elements are key factors affecting their surface condition and long-term reliability. Surface cracks are usually caused by thermal stress, mechanical stress or manufacturing defects, especially under thermal shock or thermal fatigue conditions. The low-temperature brittleness of $MoSi_2$ (fracture toughness is about 2-3 $MPa \cdot m^{1/2}$) makes it easy to generate microcracks in rapid temperature changes or mechanical vibrations. These cracks may extend along the grain boundaries, eventually leading to component fracture or failure of the SiO_2 protective film. In the "plague" temperature range of 400-700℃, surface cracks may aggravate oxidation and powdering, further deteriorating the surface condition. The coating adhesion determines whether the protective coating can adhere to the $MoSi_2$ substrate for a long time to prevent peeling or cracking. Coatings with insufficient adhesion are prone to fall off during high-temperature cycles, exposing the substrate to oxidation or corrosion environments, thereby reducing the life of the component. The formation of surface cracks is affected by many factors. Material purity is an important factor. High-purity $MoSi_2$ can reduce grain boundary impurities and reduce the probability of crack initiation. The microstructure has a significant effect on crack propagation. Dense $MoSi_2$ (such as hot-pressed sintering) has fewer pores and defects, which can effectively inhibit crack propagation, while samples with higher porosity are prone to cracking due to stress concentration. Doping modification can improve the surface crack resistance. For example, the addition of rare earth oxides (such as Y_2O_3) can enhance the grain boundary bonding force and reduce crack propagation, while certain metal doping (such as W) may increase the risk of cracks due to thermal expansion mismatch. Preparation process and surface treatment are also crucial. Surface polishing can reduce initial defects, while rough surfaces may become crack initiation points.

The research on coating adhesion mainly focuses on interface characteristics, thermal expansion matching and coating process. The difference in thermal expansion coefficient between $MoSi_2$ and coatings (such as Al_2O_3 and SiC) will cause thermal stress at the interface, affecting the adhesion. For example, SiC coatings are usually better than Al_2O_3 coatings because their thermal expansion coefficients are closer to $MoSi_2$. Interface treatment technology (such as transition layer design) can significantly improve the adhesion. For example, adding a SiC transition layer between the $MoSi_2$ substrate and the Al_2O_3 coating can alleviate the thermal stress mismatch. The coating process also has an important influence on the adhesion. The coating formed by plasma spraying has strong adhesion, but there may be micropores, while the coating generated by the CVD process is more uniform and has higher adhesion. Thermal cycling and environmental factors (such as humidity and atmosphere) will further test the adhesion. High humidity environment may cause chemical reactions at the coating interface and reduce adhesion. Studies have shown that optimizing coating thickness and interface design (such as gradient coating) can significantly improve adhesion and reduce the risk of cracks and peeling.

2.9.3 Formation and protection of surface SiO_2 oxide film

SiO_2 oxide film on the surface of the $MoSi_2$ heating element is the core of its high temperature oxidation resistance, which determines its long-term stability and service life in an oxidizing atmosphere. Above 800°C, the $MoSi_2$ surface reacts $2MoSi_2 + 7O_2 \rightarrow 2MoO_3 + 4SiO_2$ generates a dense SiO_2 film. This film has a low oxygen diffusion coefficient and good self-healing ability, which can effectively prevent oxygen from penetrating into the substrate and protect $MoSi_2$ from further oxidation erosion. In the range of 1200-1850℃, the SiO_2 film remains stable, allowing the $MoSi_2$ heating element to work for a long time in a high-temperature oxidizing atmosphere. The maximum operating temperature can reach 1850℃, and it is widely used in ceramic sintering, glass melting and other processes. However, in the "plague" temperature range of 400-700℃, $MoSi_2$ is oxidized to generate a non-protective mixture of MoO_3 and SiO_2 , resulting in loose film layer and material powderization, which seriously affects the surface protection performance. In order to avoid "plague", this temperature range is usually passed quickly in practical applications.

SiO_2 films are affected by many factors. Material purity is crucial to the quality of the film. High-purity $MoSi_2$ can produce a denser and more uniform SiO_2 film , while impurities (such as Fe and Al) may cause film defects and reduce the protective effect. Microstructure also plays an important role. Dense $MoSi_2$ (such as hot-pressed sintering) has fewer surface pores, which is conducive to the formation of a continuous SiO_2 film , while samples with high porosity may form an uneven film layer and reduce oxidation resistance. Doping modification has a dual effect on the performance of SiO_2 films. Rare earth oxides (such as Y_2O_3) can improve the adhesion and stability of the film, while certain metal doping (such as W) may reduce the quality of the film due to changes in oxidation kinetics. The atmosphere and humidity in the working environment have a significant effect on the formation and protection of SiO_2 films . In a high-humidity environment, the SiO_2 film may undergo hydration reactions to form a loose silicate structure, reducing its protective ability. In a reducing or vacuum environment, the SiO_2 film cannot be formed or is destroyed, resulting in Si volatilization and substrate degradation.

The SiO_2 film is the key to the performance of the $MoSi_2$ heating element. During long-term operation at high temperature, the SiO_2 film may become thinner due to the volatilization of Si or MoO_3 , especially at the extreme temperature close to 1850°C, the film layer may be partially damaged. Frequent thermal cycles may also cause the film layer to crack or peel off, reducing the protective effect. In order to enhance the stability of the SiO_2 film , modern $MoSi_2$ elements often use surface modification technology, such as pre-oxidation treatment to form an initial dense film layer, or add protective coatings (such as Al_2O_3 or SiC) to enhance the thermal shock resistance and durability of the film. In practical applications, maintaining a stable oxidizing atmosphere, avoiding high humidity environments, and optimizing thermal cycle parameters are effective measures to maintain the protective performance of the SiO_2 film . In the future, research directions may focus on optimizing the formation kinetics of the SiO_2 film and developing composite protective layers to further improve the surface performance and service life of $MoSi_2$ heating elements .

2.10 Surface problems of $MoSi_2$ heating elements and their solutions

Molybdenum disilicide ($MoSi_2$) heating elements are important factors affecting their high temperature performance and service life, mainly including surface cracks, "plague" oxidation, degradation of SiO_2 protective film and coating peeling. These problems are particularly significant in high temperature cycles, thermal shock or specific atmosphere environments, which may lead to degradation of component performance or even failure. Surface cracks are usually caused by thermal stress, mechanical stress or manufacturing defects. The low-temperature brittleness of $MoSi_2$ makes it easy to generate microcracks in rapid temperature changes or mechanical vibrations, which then expand into macro cracks, weakening oxidation resistance and mechanical strength. In the "plague" temperature range of 400-700℃, the surface of $MoSi_2$ is oxidized to generate a non-protective mixture of MoO_3 and SiO_2 , resulting in material pulverization and serious damage to the surface state. During long-term high-temperature operation, the SiO_2 protective film may become thinner due to Si volatilization or MoO_3 volatilization. Especially at the extreme temperature close to 1850℃, the film layer may be partially damaged, reducing the protection effect. The applied protective coating may peel off due to thermal expansion mismatch or insufficient interface bonding, exposing the substrate to oxidative or corrosive environments.

Solving the problem of surface cracks can be achieved by optimizing the preparation process and material modification. The hot pressing sintering process can improve the density of $MoSi_2$, reduce surface pores and defects, and thus reduce the probability of crack initiation. Doping with rare earth oxides (such as Y_2O_3) or alumina can enhance grain boundary strength and inhibit crack propagation. Surface polishing can reduce initial defects and reduce stress concentration. In order to deal with "plague" oxidation, in practical applications, the temperature is usually quickly raised through the 400-700℃ temperature range to reduce the generation time of non-protective oxides. In addition, pre-oxidation treatment can pre-generate a dense SiO_2 film on the surface to enhance the ability to resist "plague". In order to maintain the stability of the SiO_2 film, the adhesion of the film can be improved by adding rare earth elements, or a composite coating can be used to enhance thermal shock resistance and durability. For the problem of coating peeling, optimizing the coating process (such as chemical vapor deposition or plasma spraying) and interface design (such as adding a SiC transition layer) can improve the bonding strength and reduce thermal stress mismatch. In practical applications, controlling the heating and cooling rates, avoiding high humidity environments, and regularly checking the surface conditions are effective measures to extend the life of $MoSi_2$ heating elements .

In the future, the direction of solving surface problems may focus on the development of nanostructured coatings and multilayer composite coatings to further improve the stability of SiO_2 films and the bonding strength of coatings. In addition, intelligent monitoring technology can be used to detect surface conditions in real time, adjust operating parameters in time, and extend the service life of components. The comprehensive application of these methods can effectively alleviate the surface problems of $MoSi_2$ heating elements and improve their reliability in high-temperature applications such as ceramic sintering and glass melting.

2.11 Factors Affecting Thermodynamic Properties of $MoSi_2$ Heating Elements

The thermodynamic properties of $MoSi_2$ heating elements, including thermal conductivity, thermal expansion coefficient, specific heat capacity and thermal diffusivity, directly affect their heating efficiency, temperature uniformity and thermal shock resistance. These properties are affected by the intrinsic properties of the material (such as composition and microstructure) and the external environment (such as operating temperature and atmosphere). The thermal conductivity of $MoSi_2$ is about

45 W/(m·K) at room temperature, and drops to about 15 W/(m·K) at high temperature (1500°C), ensuring good heat transfer capacity, but the decrease in thermal conductivity with temperature will affect the rapid heating efficiency. Its thermal expansion coefficient is about 8.1×10^{-6} K^{-1}, which matches well with the ceramic matrix material and reduces thermal stress, but its low-temperature brittleness makes it easy to crack under thermal shock. The specific heat capacity is about 0.45 J/(g·K), which increases slightly at high temperature, affecting the thermal diffusivity. These thermodynamic properties jointly determine the performance of $MoSi_2$ in high-temperature furnaces.

Material purity is a key factor affecting thermodynamic properties. High-purity $MoSi_2$ can reduce phonon scattering caused by impurities (such as Fe and C), improve thermal conductivity, reduce grain boundary defects, and improve thermal stress distribution. The microstructure has a significant effect on thermodynamic properties. Dense $MoSi_2$ (such as prepared by hot pressing and sintering) has higher thermal conductivity and thermal shock resistance, while samples with high porosity have poor performance due to scattered heat and stress concentration. Doping modification can optimize thermodynamic properties. For example, adding W can slightly increase thermal conductivity, but may increase thermal stress due to thermal expansion mismatch; rare earth oxide (such as Y_2O_3) doping can enhance grain boundary strength and improve thermal shock resistance. Preparation processes such as hot pressing or reaction sintering also have an important influence on thermodynamic properties. High-density samples usually exhibit better thermal conductivity and thermal stress resistance.

The influence of the external environment on thermodynamic properties cannot be ignored. The operating temperature and atmosphere directly affect thermal conductivity, thermal expansion and thermal shock resistance by changing the surface state and internal structure of the material. In practical applications, optimizing component design (such as increasing the hot end surface area) and controlling operating conditions (such as stabilizing the temperature gradient) can improve thermodynamic performance and meet the needs of demanding applications such as ceramic sintering and semiconductor heat treatment.

2.11.1 Effect of operating temperature

The working temperature is the core factor affecting the thermodynamic properties of $MoSi_2$ heating elements, which directly determines the performance of its thermal conductivity, thermal expansion coefficient and thermal shock resistance. In the range of room temperature to 1000°C, the thermal conductivity of $MoSi_2$ drops from about 45 W/(m·K) to about 25 W/(m·K), mainly due to the enhanced phonon scattering and reduced contribution of electronic thermal conductivity at high temperatures. In the high temperature range of 1000-1850°C, the thermal conductivity further drops to about 15 W/(m·K), but it can still meet the heat transfer requirements of applications such as ceramic sintering and glass melting. The thermal expansion coefficient increases slightly at high temperatures, but remains in the range of $8\text{-}9\times10^{-6}$ K^{-1}, which matches well with the ceramic matrix and reduces thermal stress. However, the fracture toughness of $MoSi_2$ at high temperatures is low (2-3 $MPa{\cdot}m^{1/2}$), and microcracks are easily generated due to thermal stress when the temperature is rapidly raised and lowered, affecting the stability of the thermodynamic properties. High-temperature operation will also affect the formation and stability of the SiO_2 protective film. Above 800°C, the dense SiO_2 film effectively protects the substrate, but at the extreme temperature close to 1850°C, Si volatilization and MoO_3 volatilization may cause the film layer to become thinner, reducing the long-term stability of the thermodynamic properties. In the "plague" temperature range of 400-700°C, the generation of non-protective oxides will cause the material to pulverize, further deteriorating thermal conductivity and thermal shock resistance. In order to reduce the adverse effects of operating temperature, in practical applications, the stability of thermodynamic properties can be improved by optimizing the heating and cooling rates, using pre-oxidation treatment to form the initial SiO_2 film, and applying a protective coating (such as Al_2O_3 or SiC). In terms of component design, the use of U-type or W-type structures can disperse thermal stress and improve thermodynamic performance at high temperatures.

2.11.2 Influence of atmosphere

The atmosphere has a significant effect on the thermodynamic properties of $MoSi_2$ heating elements, mainly by changing the surface state and the internal structure of the material. In an oxidizing atmosphere, the SiO_2 protective film generated on the surface of $MoSi_2$ can effectively maintain the stability of the thermodynamic properties. The low oxygen diffusion coefficient of the SiO_2 film ensures the long-term consistency of thermal conductivity and thermal expansion coefficient, while protecting the substrate from oxidation corrosion. However, a high-humidity oxidizing atmosphere may cause the SiO_2 film to hydrate, forming a loose silicate structure, reducing thermal conductivity and thermal shock resistance. In a reducing atmosphere (such as H_2) or a vacuum environment, the SiO_2 film cannot be formed or is destroyed, resulting in Si volatilization and substrate degradation, a significant decrease in thermal conductivity, and increased thermal stress may induce cracks, seriously affecting the thermodynamic properties.

Inert atmospheres (such as Ar, N_2) have little effect on the thermodynamic properties of $MoSi_2$, but long-term operation may slowly form a SiO_2 film due to the presence of trace amounts of oxygen , slightly changing the thermal conductivity. Impurities in the atmosphere (such as sulfides and chlorides) may react with the surface of $MoSi_2$ to form non-protective compounds, reducing the stability of thermodynamic properties. In order to cope with the influence of the atmosphere, a stable oxidizing atmosphere should be preferred in practical applications to avoid high humidity or reducing environments. Surface coatings (such as SiC or Al_2O_3) can enhance corrosion resistance and maintain thermodynamic properties. In addition, regular inspection of the atmosphere purity and the surface state of the component, and optimization of operating parameters (such as controlling the atmosphere humidity) are effective measures to ensure the stability of the thermodynamic properties of the $MoSi_2$ heating element .

2.11.3 Effect of heating/cooling frequency

has a significant impact on the thermodynamic properties of molybdenum disilicide ($MoSi_2$) heating elements, especially in applications that require frequent thermal cycling, such as ceramic sintering furnaces, glass annealing furnaces, and metal heat treatment equipment. The thermodynamic properties of $MoSi_2$, including thermal conductivity, thermal expansion coefficient, and thermal diffusivity, are challenged by thermal stress during rapid heating/cooling cycles. Frequent thermal cycling causes thermal stresses to act repeatedly on the microstructure of $MoSi_2$, which may trigger the initiation and propagation of microcracks, especially due to its low-temperature brittleness (fracture toughness of about 2-3 MPa·$m^{1/2}$), reducing thermal conductivity and thermal shock resistance. In addition, in the "plague" temperature range of 400-700℃, rapid thermal cycling may aggravate the formation of non-protective oxides (a mixture of MoO_3 and SiO_2), leading to surface powdering and further deteriorating thermodynamic properties.

The effect of heating/cooling frequency is closely related to the temperature range and rate of the cycle. In large-scale cycles from high temperature (1200-1850℃) to low temperature (room temperature or 400-700℃), thermal stress is more significant, which may cause cracking or peeling of the SiO_2 protective film, weakening the oxidation resistance and thermal conductivity. High-frequency cycles (such as heating and cooling multiple times per hour) will accelerate fatigue damage of the microstructure and shorten the life of the component, while low-frequency cycles (such as once a day) have relatively little effect on thermodynamic properties. Material purity and microstructure are critical to tolerance to thermal cycles. High-purity $MoSi_2$ can reduce grain boundary weakening caused by impurities and reduce the risk of crack propagation. Dense microstructures (such as those prepared by hot pressing and sintering) can effectively disperse thermal stress and improve thermal fatigue resistance, while samples with higher porosity are prone to cracking due to stress concentration. Doping modification can also improve thermal cycling performance. For example, the addition of rare earth oxides (such as Y_2O_3) can enhance grain boundary strength and inhibit crack propagation. In order to mitigate the adverse effects of heating/cooling frequency, a variety of optimization measures can be taken in practical applications. Controlling the heating and cooling rates can reduce the accumulation of thermal stress and avoid rapid passage through the 400-700°C temperature range to inhibit "plague" oxidation. Surface coatings (such as Al_2O_3 or SiC) can enhance thermal shock resistance and the stability of SiO_2 films , extending thermal cycle life. Optimizing component design (such as using U -shaped or W-shaped structures) can disperse thermal stress and reduce crack initiation. Regularly checking the surface state and adjusting the thermal cycle parameters can also effectively extend the stability of the thermodynamic properties of the $MoSi_2$ heating element to meet the needs of high-frequency thermal cycle applications .

2.11.4 Influence of operating voltage

The operating voltage is a key external factor affecting the thermodynamic performance and operating stability of $MoSi_2$ heating elements, and is directly related to its heating efficiency, temperature distribution and service life. The resistivity of $MoSi_2$ has a positive temperature coefficient characteristic, which is about 2.0×10^{-5} at room temperature . Ω· cm, increases to about 4.0×10^{-5} at 1000℃ Ω· cm, about 4.5×10^{-5} at 1500℃ Ω· cm. This property enables $MoSi_2$ to adaptively adjust power output at different voltages, but it may have an adverse effect on thermodynamic properties under high voltage or unstable voltage conditions. High voltage causes the component to heat up rapidly and generate large thermal stress, especially in $MoSi_2$, which has significant low-temperature brittleness, which may induce microcracks and reduce thermal conductivity and thermal shock resistance. In addition, high voltage may cause local overheating, accelerate the volatilization of Si or MoO_3 of the surface SiO_2 protective film , make the film thinner, and weaken the oxidation resistance.

Voltage fluctuations are also an important factor affecting thermodynamic properties. Frequent voltage fluctuations can cause current instability, resulting in uneven temperature distribution inside the component, increasing thermal stress concentration, and then causing microstructural damage or surface cracks. Long-term high-voltage operation may accelerate the aging of $MoSi_2$, such as resistivity drift or grain growth, and reduce thermal diffusivity and thermal conductivity. Material purity and microstructure play an important role in tolerance to voltage effects. High-purity $MoSi_2$ can reduce local resistance unevenness caused by impurities and reduce the risk of overheating. Dense microstructures (such as those prepared by hot pressing and sintering) can improve the ability to disperse thermal stress and enhance resistance to voltage fluctuations. Doping modifications (such as adding W or Nb) can optimize resistivity and improve electrothermal stability under voltage, but oxidation resistance needs to be balanced.

To mitigate the adverse effects of the voltage used, the voltage control strategy needs to be optimized in practical applications. Using a stable power supply system and voltage regulator can reduce fluctuations and ensure uniform heating. The resistance matching design of the cold end and the hot end (such as doping the cold end with a highly conductive material) can reduce the risk of local overheating and improve energy efficiency. Applying a protective coating (such as SiC or Al_2O_3) can enhance the surface oxidation resistance and thermal stress tolerance and extend the life of the component. In addition, regular monitoring of the voltage input and the surface state of the component, combined with an appropriate heating curve design (such as slow heating), can effectively maintain the thermodynamic properties of the $MoSi_2$ heating element and meet the needs of high-precision applications such as ceramic sintering and semiconductor heat treatment.

2.11.5 Effect of current density

has an important influence on the thermodynamic properties and long-term stability of $MoSi_2$ heating elements, and directly determines its heating power, temperature distribution and material aging behavior. As a resistive heating material, the power output of $MoSi_2$ is proportional to the square of the current density ($P = I^2R$), so high current density will significantly increase the temperature of the element, affecting thermal conductivity, thermal expansion and thermal shock resistance. The thermal conductivity of $MoSi_2$ is lower at high temperature (about 15 W/(m·K) at 1500℃) than at room temperature (45 W/(m·K)). High current density may cause local overheating and generate large thermal stress, especially in $MoSi_2$ with significant low-temperature brittleness , which is easy to cause microcracks or cracking of the surface SiO_2 protective film, reducing the thermodynamic properties. In addition, high current density may accelerate the volatilization of Si or MoO_3 of the SiO_2 film , making the film thinner and weakening the oxidation resistance, especially at the extreme temperature close to 1850℃. The uniformity of current density distribution is critical to thermodynamic performance. Non-uniform current density (such as local high current density caused by component design defects or poor contact) will lead to increased temperature gradients, increased thermal stress and crack risks, and reduced thermal diffusivity. Long-term high current density operation may cause resistivity drift or microstructural degradation of $MoSi_2$ (such as grain growth or grain boundary weakening), further affecting thermal conductivity and thermal shock resistance. Material purity and microstructure have a significant effect on current density tolerance. High-purity $MoSi_2$ can reduce local resistance unevenness caused by impurities and reduce the risk of overheating. Dense microstructures (such as hot pressing and sintering preparation) can improve thermal stress dispersion capabilities and enhance resistance to current density shock. Doping modification (such as adding Y_2O_3) can optimize grain boundary structure, stabilize resistivity, and improve thermodynamic properties under current density.

In order to mitigate the adverse effects of the current density used, it is necessary to optimize the component design and operating conditions in practical applications. U-shaped or W-shaped components with uniform cross-section design can ensure uniform current density distribution and reduce local overheating. Resistance matching between the cold end and the hot end (such as doping the cold end with highly conductive materials) can reduce current density concentration and improve energy efficiency. Applying a protective coating (such as Al_2O_3 or SiC) can enhance the surface oxidation resistance and thermal stress resistance and extend the life of the component. Using a current controller to stabilize the input current, avoid excessive current density, and regularly check the surface state and electrical properties of the component are effective measures to maintain the stability of the thermodynamic properties of the $MoSi_2$ heating element. These optimization strategies can meet the needs of high-power applications such as glass melting and metal heat treatment.

2.11.6 Impact of installation method

Has an important influence on the thermodynamic performance and service life of molybdenum disilicide ($MoSi_2$) heating elements, which is directly related to the distribution of thermal stress, temperature uniformity and mechanical stability. The thermodynamic properties of $MoSi_2$, including thermal conductivity, thermal expansion coefficient and thermal diffusivity, may be adversely affected by thermal or mechanical stress under inappropriate installation methods. Common installation methods include vertical suspension, horizontal support and clamping, each of which has different effects on thermodynamic properties. Vertical suspension is the most common installation method for $MoSi_2$ heating elements. It is suitable for U-shaped or W-shaped elements.

It can reduce mechanical constraints and allow free thermal expansion of the elements at high temperatures, thereby reducing thermal stress. However, if the suspension point is not designed properly (such as stress concentration at the contact point), it may cause local cracks and reduce thermal conductivity and thermal shock resistance. Horizontal support installation is usually used for straight rod type elements, but it is necessary to ensure that the support material (such as high purity alumina) matches the thermal expansion coefficient of $MoSi_2$, otherwise stress concentration may be caused by thermal expansion mismatch, affecting the thermal diffusivity. The clamping fixation method is more common in small furnaces, but excessive clamping force may cause microcracks in $MoSi_2$ due to low-temperature brittleness, thus weakening the thermodynamic properties.

The installation method also affects the stability and oxidation resistance of the surface SiO_2 protective film. Uneven installation stress may cause cracking of the surface film layer, especially in the "plague" temperature range of 400-700℃, where cracks may aggravate the formation of non-protective oxides, reduce thermal conductivity and thermal shock resistance. In addition, the installation method has an indirect effect on current distribution and temperature uniformity. For example, poor contact may lead to increased local current density, causing overheating and accelerating SiO_2 film degradation. In order to optimize the impact of the installation method, an installation design that matches the furnace type should be selected in actual applications, such as using high-purity ceramic supports to reduce thermal expansion mismatch and using flexible clamping to reduce mechanical stress. Ensuring good contact between the installation point and the $MoSi_2$ cold end can improve current uniformity and reduce local overheating. Regularly checking the wear and looseness of the installation point, combined with a reasonable heating and cooling rate (such as 5-10℃/min), can effectively maintain the thermodynamic properties of the $MoSi_2$ heating element and extend its life in applications such as ceramic sintering and glass melting.

2.11.7 Impact of Component Quality and Purity

$MoSi_2$ heating elements are the core intrinsic factors affecting their thermodynamic properties, directly determining their thermal conductivity, thermal expansion coefficient, thermal shock resistance and long-term stability. High-purity $MoSi_2$ (purity is usually ≥99.5%) can significantly improve thermodynamic properties. Its thermal conductivity is about 45 W/(m·K) at room temperature and about 15 W/(m·K) at 1500℃. Its thermal diffusion coefficient is about 1.6×10^{-5} m^2/s at room temperature and about 0.8×10^{-5} m^2/s at 1500℃. High-purity materials can reduce phonon scattering and grain boundary weakening caused by impurities (such as Fe, Al, and C), thereby improving thermal conductivity and thermal stress dispersion capabilities. The presence of impurities can lead to local resistance inhomogeneity, increase thermal stress concentration, reduce thermal shock resistance, and even induce microcracks, especially in the low-temperature brittle stage of $MoSi_2$. In addition, impurities may react with oxygen to form non-protective oxides, weakening the density of the surface SiO_2 protective film, reducing the stability of oxidation resistance and thermodynamic properties, especially in the "plague" temperature range of 400-700℃, where impurities will aggravate the pulverization of the material.

$MoSi_2$ prepared by hot pressing sintering has high density (close to more than 98% of the theoretical density), low porosity, and better thermal conductivity and thermal shock resistance than samples prepared by reaction sintering or self-propagating high temperature synthesis (SHS). Components with high porosity have low thermal conductivity due to pore scattering heat and stress concentration, and are prone to cracking during thermal cycles, reducing the thermal diffusion coefficient.

High-quality $MoSi_2$ components must also have a uniform microstructure and a moderate grain size (usually 10-50 μm). Excessively large grains may lead to a decrease in grain boundary strength, while too small grains may increase grain boundary scattering and reduce thermal conductivity. Doping modification can further optimize the effects of quality and purity. For example, the addition of rare earth oxides (such as Y_2O_3) can enhance grain boundary bonding and improve thermal shock resistance, while high-purity dopants can avoid the introduction of additional impurities .

In order to improve the quality and purity of components, high-purity raw materials (such as high-purity Mo and Si powders) must be selected and the preparation process must be strictly controlled in practical applications. Hot pressing sintering or plasma spraying can improve density and reduce porosity and defects. Quality control links (such as X-ray diffraction and scanning electron microscopy) can ensure the purity of components and the uniformity of microstructure. Applying protective coatings (such as SiC or Al_2O_3) can further compensate for the lack of oxidation resistance of low-purity materials. Regular inspection of the surface state and performance of the components, combined with stable operating conditions (such as avoiding high humidity or reducing atmosphere), can maximize the thermodynamic properties of $MoSi_2$ heating elements to meet the needs of high-demand applications such as semiconductor heat treatment and metal heat treatment.

2.11.8 Effect of coating protection treatment

Coating protection treatment has an important influence on the thermodynamic properties of $MoSi_2$ heating elements, and can significantly enhance its oxidation resistance, thermal shock resistance and thermal conductivity stability. Commonly used protective coatings include oxide coatings (such as Al_2O_3, ZrO_2), carbide coatings (such as SiC) and composite coatings (such as Al_2O_3-SiC), which form a dense protective layer to make up for the deficiency of SiO_2 film on the surface of $MoSi_2$ under extreme conditions. Al_2O_3 coating can effectively improve oxidation resistance and maintain the stability of thermal conductivity (about 15 W/(m·K) at 1500°C) due to its high melting point (about 2050°C) and low oxygen diffusion coefficient (about 10^{-14} cm^2/s at 1500°C), especially in high temperature oxidizing atmosphere (1200-1850°C).

SiC coating has a better match between thermal expansion coefficient (about 4.5×10^{-6} K^{-1}) and $MoSi_2$ (about 8.1×10^{-6} K^{-1}), which reduces thermal stress mismatch and improves thermal shock resistance, making it suitable for high thermal cycle environments such as ceramic sintering furnaces. Composite coatings combine the advantages of multiple materials. For example, Al_2O_3-SiC coatings have both high oxidation resistance and thermal shock resistance, significantly improving the long-term stability of thermodynamic properties.

The improvement of thermodynamic properties by coatings is closely related to their adhesion, thickness and uniformity. High-quality coatings (such as those prepared by chemical vapor deposition (CVD)) have high adhesion and uniformity, can effectively disperse thermal stress, and maintain the stability of the thermal diffusion coefficient (about 0.8×10^{-5} m^2/s at 1500°C). Too thick coatings (>100 μm) may cause cracking due to thermal expansion mismatch and reduce thermal conductivity, while too thin coatings (<10 μm) may not provide adequate protection. The coating process also has a significant impact on thermodynamic properties. Plasma spraying can form thick and dense coatings, which are suitable for industrial-scale applications, but may have micropores and slightly reduce thermal conductivity; thin coatings generated by CVD processes are more uniform, have low thermal stress, and are suitable for high-precision requirements. Coatings can also reduce the impact of "plague" oxidation (400-700°C). For example, SiC coatings can inhibit the formation of non-protective MoO_3 and protect thermodynamic properties.

The long-term stability of the coating is affected by the working environment. In a high humidity environment, the Al_2O_3 coating may undergo hydration reaction, reducing thermal conductivity; in a reducing or vacuum environment, the coating may deteriorate due to Si volatilization, affecting the thermal diffusion coefficient. In order to optimize the impact of coating protection treatment, it is necessary to select the appropriate coating type and process according to the application requirements in actual applications. For example, high-purity CVD coatings are preferred for semiconductor heat treatment furnaces, and thick SiC coatings can be used for glass melting furnaces. Interface design (such as adding a SiC transition layer) can improve bonding and reduce the risk of peeling. Regular inspection of coating integrity and surface condition, combined with a stable oxidizing atmosphere and appropriate heating and cooling rates (such as 5-10°C/min), can maximize the protective effect of the coating on the thermodynamic properties of the $MoSi_2$ heating element and extend its life in high-temperature applications.

2.12 CTIA GROUP LTD $MoSi_2$ Heating Element MSDS

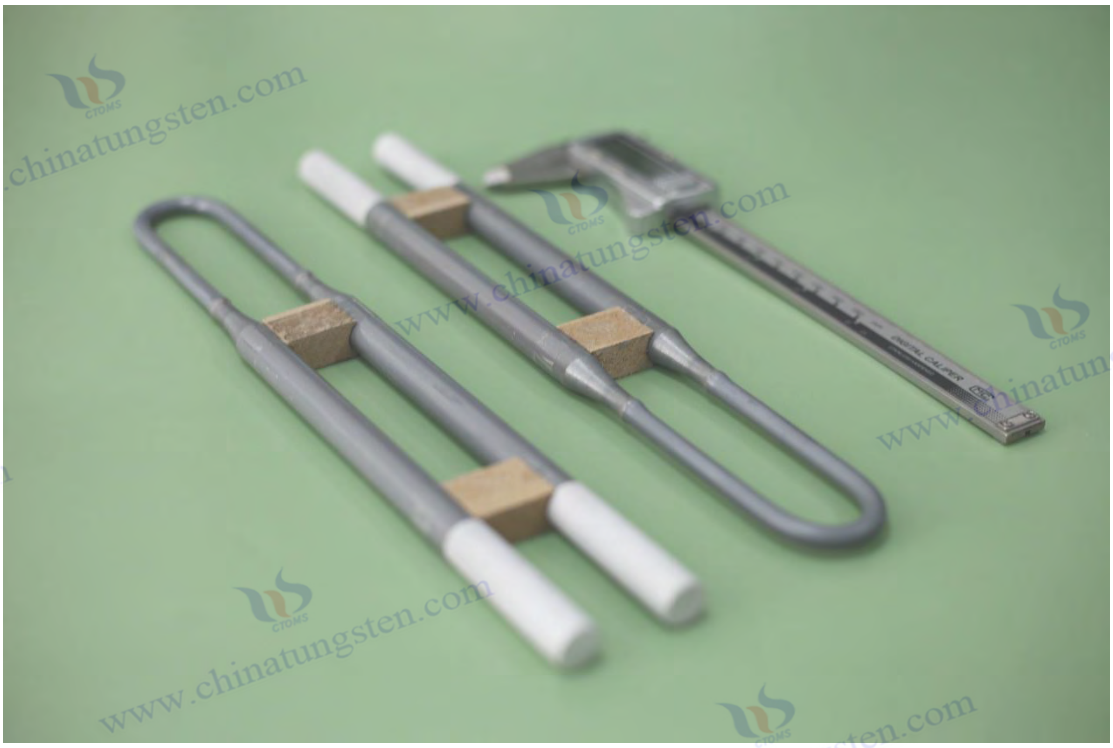
provides information on the safe use, storage and handling of molybdenum disilicide ($MoSi_2$) heating elements produced by CTIA GROUP LTD. $MoSi_2$ is an intermetallic compound with excellent high-temperature oxidation resistance and electrical conductivity. It is widely used in high-temperature industrial and laboratory furnaces (such as ceramic sintering, glass melting and metal heat treatment). The following is a detailed description of the MSDS content of CTIA GROUP LTD $MoSi_2$ heating elements based on the characteristics of $MoSi_2$ materials and industry standards, including its physical and chemical properties, hazard identification, safe operation and emergency measures.

Material identification and composition : CTIA GROUP LTD's $MoSi_2$ heating elements are mainly composed of molybdenum disilicide (chemical formula: $MoSi_2$, CAS number: 12136-78-6), with a purity of usually ≥99.5%, and may contain trace additives (such as rare earth oxides or aluminum oxide) to enhance performance. $MoSi_2$ is a ceramic material with a gray metallic appearance, a tetragonal α-type (C11b-type) crystal structure, a density of about 6.24 g/cm³, a melting point of about 2030°C, and electrical conductivity. The heating element is usually U-shaped, W-shaped or a straight rod, and a dense SiO_2 protective film is formed on the surface under a high-temperature oxidizing atmosphere. Possible impurities include Fe, Al, C, etc., and the content is usually less than 0.1%, depending on the production batch and doping process.

Hazard identification : $MoSi_2$ heating elements are relatively safe under normal high temperature use, but the following hazards may exist under certain conditions. In terms of physical hazards, $MoSi_2$ is brittle at room temperature and can easily break due to mechanical impact or improper handling, resulting in sharp fragments that may cause cuts. In terms of chemical hazards, $MoSi_2$ will undergo low-temperature oxidation in the "plague" temperature range of 400-700°C, generating a mixture of MoO_3 and SiO_2 , which may release trace amounts of MoO_3 vapor (which can irritate the respiratory tract and eyes). In a reducing or vacuum environment, Si volatilization may cause material degradation and release silicon vapor, which should be avoided from inhalation. In terms of environmental hazards, $MoSi_2$ itself has little impact on the environment, but discarded components need to be treated as hazardous waste to avoid pollution.

Safety operation and protective measures : To ensure the safe use of CTIA GROUP LTD $MoSi_2$ heating elements, the MSDS provides the following operating guidelines. Wear protective gloves (such as high temperature resistant gloves) and goggles when handling, avoid direct contact with sharp edges, and prevent mechanical damage or debris from injuring people. Appropriate fixing methods should be used during installation (such as vertical suspension or flexible clamping) to avoid excessive mechanical stress causing breakage. When using, ensure that the power supply system is proportional control, phase trigger type, and has a current limiting function to avoid non-proportional switching or "sudden" power supply methods from damaging the components. When storing, it should be placed in a dry, non-corrosive gas environment to avoid surface corrosion caused by moisture or acidic atmosphere.

Storage and transportation : $MoSi_2$ heating elements need to be stored in a dry and clean environment, with the temperature controlled at 5-35°C and the relative humidity below 70%. Avoid contact with acidic substances or high humidity environments to prevent surface corrosion or degradation of the SiO_2 film. Use foam or wooden boxes for transportation, and fix the components to prevent breakage due to vibration or impact. The packaging should be marked with "fragile" and "moisture-proof" signs, and an MSDS document should be attached for reference. During transportation, dangerous goods transportation regulations (such as UN3077, environmentally hazardous substances) must be observed to ensure safe arrival.



CTIA GROUP LTD Silicon Molybdenum Rod

Chapter 3 Structure and Design of $MoSi_2$ Heating Elements

3.1 Common structures of $MoSi_2$ heating elements

Molybdenum disilicide ($MoSi_2$) heating elements are widely used in high-temperature industrial furnaces and laboratory equipment due to their excellent high-temperature oxidation resistance, electrical conductivity and maximum operating temperature. The structural design directly affects the heating efficiency, temperature uniformity, thermal shock resistance and service life. Common structures of $MoSi_2$ heating elements include U-type, W-type, L-type, straight rod type and customized shapes, among which U-type and W-type are the most popular due to their efficient heat distribution and flexible installation methods. These structures usually consist of a hot end (heat-generating part) and a cold end (connecting part). The hot end generates heat at high temperature, and the cold end reduces resistance by doping with highly conductive materials (such as aluminum or tungsten) to ensure the stability of the connection with the power supply. The structural design of $MoSi_2$ elements needs to comprehensively consider the furnace size, heating power, thermal cycle frequency and installation method to meet the needs of different applications such as ceramic sintering, glass melting, and metal heat treatment.

The optimization of structural design is crucial to the performance of $MoSi_2$ heating elements. The length, cross-sectional dimensions and connection method of the hot and cold ends need to be precisely matched to ensure uniform current distribution and avoid local overheating. The diameter of the hot end is usually 6-12 mm, and the diameter of the cold end is 1.5-2 times that of the hot end to reduce the cold end temperature and extend the service life. The geometric shape of the element (such as the bending radius of the U-type or W-type) affects the distribution of thermal stress. Reasonable bending design can reduce the risk of thermal shock cracks. Material purity (usually ≥99.5%) and preparation process (such as hot pressing and sintering) have a significant impact on structural integrity. High-purity and dense $MoSi_2$ can reduce micro defects and improve thermal fatigue resistance. Surface treatment (such as polishing or coating) can also enhance oxidation resistance and thermodynamic properties. In practical applications, the structural selection needs to be customized according to the space in the furnace, temperature distribution requirements and installation constraints. For example, the U-type is suitable for small furnaces, and the W-type is suitable for large furnaces to provide more uniform heating.

3.1.1 U-shaped $MoSi_2$ heating element

U-shaped $MoSi_2$ heating elements are one of the most common structures and are widely used in small to medium-sized high-temperature furnaces, such as laboratory box furnaces and ceramic sintering furnaces, due to their simple, compact design and efficient heating performance. The structure of the U-shaped element consists of two parallel hot ends connected by a U-shaped bend, and the cold end is located on the top of the hot end and connected to the power supply. The main advantage of the U-shaped design is that its hot end can provide a concentrated high-temperature zone, which is suitable for applications that require local high heat density, such as oxidizing atmosphere sintering with a maximum temperature of up to 1800°C. The hot end length of the U-shaped element is usually 100-500 mm, and the specific length is customized according to the furnace size and power requirements. The hot end diameter is 6-9 mm and the cold end diameter is 12-18 mm to ensure low resistance and efficient current transmission.

The thermodynamic performance of the U-shaped element benefits from its compact geometry. The distance between the hot ends (usually 20-50 mm) optimizes temperature uniformity and reduces thermal stress concentration. The bending radius of the U-shaped structure needs to be precisely designed. Too small a radius may cause stress concentration and increase the risk of thermal shock cracks, while too large a radius may reduce heating efficiency. The positive temperature coefficient resistivity of $MoSi_2$ (about 2.0×10^{-5} at room temperature) Ω· cm, about 4.5×10^{-5} at 1500°C Ω· cm) enables the U-shaped element to automatically adjust power at high temperatures, making it suitable for precise temperature control applications. However, U-shaped elements may produce microcracks due to stress accumulation at the connection between the hot end and the cold end during frequent thermal cycles, especially in $MoSi_2$, which has significant low-temperature brittleness (fracture toughness is about 2-3 MPa· $m^{1/2}$). To improve the thermal shock resistance and life of U-shaped elements, hot pressing and sintering processes can increase material density, and surface coatings (such as SiC or Al_2O_3) can enhance oxidation resistance and thermal fatigue resistance.

In terms of installation, U-shaped elements are usually suspended vertically, and the cold end is fixed by a ceramic clamp to reduce mechanical stress. During installation, it is necessary to ensure that the cold end is in good contact with the power supply to avoid local overheating. In practical applications, U-shaped elements need to avoid quickly passing through the "plague" temperature range of 400-700°C to prevent the generation of non-protective oxides (a mixture of MoO_3 and SiO_2) that cause surface powdering . Maintenance of U-shaped elements includes regular inspection of the integrity of bends and connection points, and monitoring the state of the SiO_2 protective film to ensure its long-term stability in an oxidizing atmosphere.

3.1.2 W-type $MoSi_2$ heating element

W-type $MoSi_2$ heating elements are widely used in large high-temperature furnaces or scenarios requiring uniform temperature fields, such as glass melting furnaces, industrial ceramic sintering furnaces, and metal heat treatment equipment, due to their complex geometry and larger heating area. The structure of the W-type element consists of multiple parallel hot ends connected by continuous W-shaped bends, usually containing three or more hot ends, and the cold ends are located on both sides or the top and connected to the power supply. Its main advantage is that it can cover a larger furnace area and provide a more uniform temperature distribution, which is suitable for large furnaces or multi-zone heating needs. The hot end length of the W-type element is usually 200-1000 mm, the diameter is 6-12 mm, and the cold end diameter is 12-24 mm. The specific size is customized according to the power demand and furnace design. The heating power density is usually 15-20 W/cm² (at 1700°C), which can meet the requirements of high power output while maintaining temperature uniformity.

The thermodynamic performance of the W-type element benefits from its multi-hot-end design. The spacing between multiple hot ends (usually 30-60 mm) can optimize the distribution of heat radiation and reduce local overheating and thermal stress concentration. The bending radius of the W-type structure needs to be precisely controlled. A too small radius may lead to stress concentration and increase the risk of thermal shock cracking, while a too large radius may reduce heating efficiency. The positive temperature coefficient (PTC) resistivity of $MoSi_2$ enables the W-type element to adaptively adjust the power at high temperatures to ensure precise temperature control and stability. However, the W-type element may produce microcracks due to stress accumulation at multiple bends and hot-end-cold-end connection points during frequent thermal cycles, especially when the low-temperature brittleness of $MoSi_2$ is significant (fracture toughness is about 2-3 $MPa \cdot m^{1/2}$). The hot pressing sintering process can increase the density of the material (close to more than 98% of the theoretical density), reduce micro defects, and enhance thermal fatigue resistance. Surface coatings (such as SiC or Al_2O_3) can further improve oxidation resistance and thermal shock resistance, extending the service life of components in high temperature oxidizing atmospheres (up to 1800-1850°C) .

In terms of installation, W-type components are usually suspended vertically or supported horizontally, with the cold end fixed by a high-purity ceramic clamp or support to reduce mechanical stress and allow thermal expansion. During installation, it is necessary to ensure that the cold end is in good contact with the power supply to avoid local overheating caused by contact resistance. The complex shape of the W-type component requires higher installation accuracy, such as ensuring that each hot end is arranged symmetrically to maintain uniform current distribution. In practical applications, it is necessary to avoid quickly passing through the "plague" temperature range of 400-700°C to prevent the formation of non-protective oxides (a mixture of MoO_3 and SiO_2) that cause surface powdering. Maintenance of W-type components requires regular inspection of the integrity of the bends, connection points and surface SiO_2 protective film to ensure its long-term stability in an oxidizing atmosphere. Maintenance of W-type components also includes monitoring the cold end temperature (usually kept below 400°C) to prevent overheating from causing degradation of the connection points.

To optimize the performance of W-type elements, the temperature distribution requirements of a specific furnace type can be met by increasing the number of hot ends or adjusting the hot end spacing during design. For example, in a large glass melting furnace, a multi-hot-end W-type element can be used to achieve uniform heating over a wide area. Surface polishing or coating can reduce surface defects and improve thermal shock resistance and oxidation resistance. In practical applications, the installation of W-type elements should take into account the heat flow dynamics of the furnace, and the elements should be arranged reasonably to avoid heat concentration or insufficient heat. Regularly cleaning the inside of the furnace to prevent impurities from contaminating the surface of the element is also an important measure to extend the life of the W-type element. The complex structure of the W-type element gives it a significant advantage in use in large industrial furnaces, but it also places higher requirements on manufacturing accuracy and installation technology.

3.1.3 Spiral $MoSi_2$ Heating Element

The spiral $MoSi_2$ heating element is a special structure suitable for applications that require high heat density and compact heating area, such as small laboratory tube furnaces, thermal analysis equipment or specific industrial furnaces. The structure of the spiral element consists of a $MoSi_2$ rod wound into a spiral hot end, and the cold end is located at both ends of the spiral for connecting the power supply. Its main advantage is that it can provide high thermal power in a limited space. The spiral shape increases the surface area of the hot end and enhances the thermal radiation efficiency, which is suitable for applications that require rapid heating and precise temperature control. The hot end diameter of the spiral element is usually 4-9 mm, and the number of spiral turns and pitch (usually 5-20 mm) are designed according to the furnace size and power requirements. The cold end diameter is 8-18 mm to ensure low resistance and efficient current transmission. The heating power density can reach 20-25 W/cm^2 (at 1700°C), which is higher than U-type and W-type, and is suitable for high-temperature local heating scenarios.

The thermodynamic performance of spiral elements is due to their high surface area and compact design. The spiral structure can provide uniform heat radiation and reduce temperature gradients, which is suitable for cylindrical heating needs in tube furnaces. However, the complex geometry of the spiral shape increases the difficulty of manufacturing. The spiral curvature and pitch need to be precisely controlled. Too tight a spiral may cause thermal stress concentration and increase the risk of cracks, especially in the low-temperature brittle stage of $MoSi_2$ (fracture toughness is about 2-3 $MPa \cdot m^{1/2}$). The positive temperature coefficient resistivity of $MoSi_2$ enables spiral elements to adaptively adjust power at high temperatures to ensure temperature control accuracy. To improve thermal shock resistance and life, the hot pressing sintering process can increase the density of the material (close to more than 98% of the theoretical density) and reduce micro defects. Surface coatings (such as SiC or Al_2O_3 , with thermal expansion coefficients of approximately $4.5\times10^{-6}K^{-1}$ and $8\times10^{-6}K^{-1}$, respectively) can enhance oxidation resistance and thermal fatigue resistance, extending the service life of components in high-temperature oxidizing atmospheres (up to 1800°C) .

In terms of installation, spiral elements are usually fixed horizontally or vertically, and the cold end is fixed by a high-purity ceramic support. It is necessary to ensure that the spiral part is not mechanically constrained to allow thermal expansion. Special attention should be paid to the uniformity of the spiral structure during installation to avoid deformation or cracks caused by installation stress. In practical applications, it is necessary to quickly pass through the "plague" temperature range of 400-700°C to prevent the generation of non-protective oxides (a mixture of MoO_3 and SiO_2) and cause surface powdering. Maintenance of spiral elements requires regular inspection of the spiral pitch, cold end connection points and the integrity of the surface SiO_2 protective film to ensure its stability in an oxidizing atmosphere. Due to the high manufacturing cost of spiral elements and strict requirements on installation accuracy, their application is mostly concentrated in high-precision laboratory equipment or special industrial furnaces.

3.1.4 Straight rod type $MoSi_2$ heating element

The straight rod type $MoSi_2$ heating element is a simple, linear structure suitable for furnace types that require long-distance linear heating, such as tunnel furnaces, continuous heat treatment furnaces or some large industrial furnaces. The structure of the straight rod type element consists of a single straight hot end, and the cold end is located at both ends or one end to connect to the power supply. Its main advantages are simple structure, low manufacturing cost, easy large-scale production and installation, and suitable for covering long-distance heating areas. The hot end length of the straight rod type element is usually 300-2000 mm, the diameter is 6-12 mm, and the cold end diameter is 12-24 mm. The specific size is customized according to the furnace length and power requirements. The heating power density is usually 15-18 W/cm² (at 1700°C), which is suitable for uniform heating applications with medium and low power density.

The thermodynamic performance of straight rod-type elements is limited by their linear design. The temperature distribution along the length of the hot end may not be as uniform as that of U-type or W-type. Especially when heating over a long distance, the phenomenon of high temperature in the middle and low temperature at both ends may occur. To improve the temperature uniformity, the resistance distribution can be optimized by adjusting the hot end diameter or segmented doping. The positive temperature coefficient resistivity of $MoSi_2$ (about 2.0×10^{-5} at room temperature) Ω· cm, about 4.5×10^{-5} at 1500°C Ω· cm) enables straight rod-type components to adaptively adjust power at high temperatures, but their linear structure may produce microcracks due to stress concentration at both ends of the hot end during frequent thermal cycles, especially when the low-temperature brittleness of $MoSi_2$ is significant (fracture toughness is about 2-3 MPa·$m^{1/2}$). The hot pressing sintering process can increase the material density, reduce micro defects, and enhance thermal shock resistance and thermal fatigue resistance. Surface coatings (such as SiC or Al_2O_3) can further improve oxidation resistance and surface stability, extending the service life of components in high-temperature oxidizing atmospheres (up to 1800°C).

In terms of installation, straight rod-type elements are usually supported horizontally or suspended vertically, and the cold end is fixed by a high-purity ceramic clamp. It is necessary to ensure that the support points are evenly distributed to avoid sagging or breaking of the element. During installation, special attention should be paid to the contact quality between the cold end and the power supply to avoid local overheating caused by contact resistance. In practical applications, it is necessary to quickly pass through the "plague" temperature range of 400-700°C to prevent the generation of non-protective oxides and cause surface powdering. To maintain straight rod-type elements, it is necessary to regularly check the integrity of the hot end surface, the cold end connection point and the SiO_2 protective film, and monitor the cold end temperature (usually kept below 400°C) to prevent overheating and degradation. Due to the simple structure of straight rod-type elements, their manufacturing and maintenance costs are low, but the requirements for temperature uniformity are high, and the layout needs to be optimized in combination with the furnace design.

3.1.5 Comparison of U-shaped, W-shaped and straight structural designs

U-shaped, W-shaped and straight rod-shaped $MoSi_2$ heating elements are the most common structures among $MoSi_2$ heating elements, each with its own characteristics, suitable for different furnace types and application scenarios. U-shaped elements are known for their compact design and centralized heating capacity. The hot end length is usually 100-500 mm, the diameter is 6-9 mm, and the power density can reach 20 W/cm² (at 1700°C). They are suitable for small to medium-sized furnaces (such as laboratory box furnaces and ceramic sintering furnaces) that require local high heat density. Its advantages are simple structure, easy installation, and high thermal efficiency, but the hot end covers a small area, and the temperature uniformity is limited by the hot end spacing (usually 20-50 mm). Microcracks are prone to occur at the connection between the hot end and the cold end during frequent thermal cycles. W-shaped elements provide a larger heating area with a multi-hot end design. The hot end length is 200-1000 mm, the diameter is 6-12 mm, and the power density is 15-20 W/cm². They are suitable for large furnaces (such as glass melting furnaces and industrial ceramic sintering furnaces) that require a uniform temperature field. Its advantages are more uniform temperature distribution and strong resistance to thermal stress, but it is complex to manufacture, costly, and multiple bends increase the risk of thermal shock cracks. Straight rod type elements are known for their linear structure, with a hot end length of 300-2000 mm, a diameter of 6-12 mm, and a power density of 15-18 W/cm², which is suitable for tunnel furnaces or continuous heat treatment furnaces with long-distance linear heating. Its advantages are low manufacturing cost and simple installation, but poor temperature uniformity, and cracks are easily generated at both ends of the hot end due to stress concentration.

From the perspective of thermodynamic properties, the thermal conductivity (about 45 W/(m·K) at room temperature and about 15 W/(m·K) at 1500°C) and thermal expansion coefficient (about 8.1×10^{-6} K^{-1}) of the three structures are similar, but the geometric shape affects the distribution of thermal stress. The bending design of the U-type and W-type can disperse thermal stress, and the thermal shock resistance is better than that of the straight rod type, but the straight rod type has higher mechanical stability due to the lack of bending stress concentration points during long-distance heating.

In terms of oxidation resistance, all three structures rely on the surface SiO_2 protective film (the oxygen diffusion coefficient is about 10^{-13} cm^2/s at 1500°C), but the W-type has a larger surface area, and the formation and maintenance of the SiO_2 film is more uniform, and the oxidation resistance is slightly better. The straight rod type may cause local SiO_2 film degradation due to uneven temperature during long-distance heating . In terms of thermal cycling performance, U-type and W-type are prone to microcracks in frequent thermal cycles due to their complex geometry, while the straight rod type is more resistant to thermal fatigue due to its simple structure, but the temperature distribution needs to be optimized.

In terms of installation and maintenance, U-shaped elements are suitable for vertical hanging, and the installation is simple, but attention should be paid to the cold end contact; W-shaped elements need to be installed precisely and symmetrically, and the maintenance is complicated, but they are suitable for large furnaces; straight rods are flexible to install, but they need to be evenly supported to prevent sagging. The manufacturing process has similar effects on the three structures. Hot pressing and sintering can improve the density (close to 98%), and surface coatings (such as SiC or Al_2O_3) can enhance oxidation resistance and thermal shock resistance. When choosing, the U-type is suitable for small high-precision furnaces, the W-type is suitable for large uniform heating furnaces, and the straight rod type is suitable for long-distance linear heating. It needs to be considered comprehensively according to the furnace design, power requirements and thermal cycle frequency.

3.2 Dimensional design of $MoSi_2$ heating elements

molybdenum disilicide ($MoSi_2$) heating elements is the key to optimizing their performance, which directly affects the heating efficiency, temperature distribution, thermal shock resistance and service life. The size of $MoSi_2$ heating elements is usually determined by the diameter and length of the hot end and the cold end, as well as the ratio of the hot end to the cold end. Common specifications include Φ6/12 (hot end diameter 6 mm, cold end diameter 12 mm) and Φ9/18 (hot end diameter 9 mm, cold end diameter 18 mm). These size designs need to be determined comprehensively based on the furnace size, power requirements, thermal cycle frequency and installation method to ensure efficient heating and long-term stability in a high-temperature oxidizing atmosphere. The Φ6/12 specification is suitable for small and medium-sized furnaces (such as laboratory box furnaces and ceramic sintering furnaces). Its hot end diameter is small and the power density is high, which is suitable for applications that require rapid heating and centralized heating. The Φ9/18 specification is suitable for large furnaces (such as glass melting furnaces, industrial heat treatment furnaces). It has a larger hot end diameter and a slightly lower power density (usually 15-20 W/cm^2), but it can provide a more uniform temperature distribution and higher mechanical strength, and is suitable for large area or high load heating scenarios.

The core goal of size design is to balance the electrothermal and mechanical properties of the hot end and the cold end. The hot end diameter determines the resistance and heating power. Smaller hot ends (such as 6 mm) have higher resistance and are suitable for high power density applications, but have lower thermal shock resistance and mechanical strength. Larger hot ends (such as 9 mm) have lower resistance and moderate power density, but better thermal shock resistance and life. The cold end diameter is usually 1.5-2 times that of the hot end (such as 6/12 or 9/18), and the resistivity is reduced by doping with highly conductive materials (such as aluminum or tungsten) (about 0.5×10^{-5} Ω· cm, at room temperature), to ensure that the cold end temperature remains below 400°C to prevent overheating and degradation. The hot end length (usually 100-1000 mm) needs to be customized according to the furnace depth and heating area. Too short may cause heat concentration, and too long may cause uneven temperature. The cold end length (usually 50-300 mm) needs to be long enough to pass through the furnace wall to ensure stable connection with the power supply and avoid heat conduction from the hot end to the cold end.

The size design also needs to consider the thermodynamic properties of $MoSi_2$. Its thermal conductivity (about 45 W/(m·K) at room temperature and about 15 W/(m·K) at 1500°C) and thermal expansion coefficient (about 8.1×10^{-6} K^{-1} , room temperature to 1000°C) affect the distribution of thermal stress. Smaller diameter hot ends (such as 6 mm) are prone to thermal stress concentration during rapid thermal cycles, leading to microcracks, especially in the low-temperature brittle stage of $MoSi_2$ (fracture toughness is about 2-3 $MPa\cdot m^{1/2}$). Larger diameter hot ends (such as 9 mm) can better disperse thermal stress and improve thermal shock resistance. The preparation process is crucial to dimensional accuracy. Hot pressing and sintering can ensure component density (close to 98%) and dimensional uniformity, and reduce micro defects. Surface coatings (such as SiC or Al_2O_3) can enhance oxidation resistance and thermal fatigue resistance, and extend the reliability of dimensional design. In practical applications, size selection needs to be optimized in combination with furnace type and operating conditions. For example, Φ6/12 is suitable for high-precision laboratory furnaces, and Φ9/18 is suitable for large industrial furnaces. It is necessary to avoid quickly passing through the "plague" temperature range of 400-700°C to prevent surface powdering.

3.3 Optimal design of thermal field and cold end structure

The optimization design of the thermal field and cold end structure of $MoSi_2$ heating elements is the key to achieving efficient heating, uniform temperature distribution and long life. The thermal field design aims to ensure that the temperature distribution in the furnace meets the process requirements (such as ±5°C accuracy of ceramic sintering), which is achieved by optimizing the hot end layout, shape and power density. The thermal conductivity of $MoSi_2$ (about 15 W/(m·K) at 1500°C) and the positive temperature coefficient resistivity (about 4.5×10^{-5} at 1500°C) are very high. Ω· cm) requires the thermal field design to accurately match the number and spacing of hot ends. For example, the hot end spacing of U-shaped elements (20-50 mm) is suitable for centralized heating of small furnaces, and the multiple hot end spacing of W-shaped elements (30-60 mm) is suitable for uniform heating of large furnaces. Thermal field optimization also needs to consider thermal radiation and convection. The surface area and arrangement of the hot ends (such as symmetrical layout) directly affect the heat distribution. Increasing the number of hot ends or using spiral elements can improve the uniformity of the thermal field, but it will increase manufacturing complexity. The power density design needs to be moderate (15-25 W/cm² at 1700°C). Too high a power density may cause local overheating and reduce the stability of the SiO_2 protective film.

The cold end structure optimization aims to reduce the cold end temperature (usually ≤400°C) and improve the electrical connection stability and component life. The cold end is doped with highly conductive materials (such as aluminum) to reduce the resistivity (about 0.5×10^{-5} Ω· cm), to reduce heat generation, and its diameter (12-24 mm) is 1.5-2 times that of the hot end to enhance heat dissipation. The length of the cold end (50-300 mm) needs to be long enough to pass through the furnace wall, enter the low temperature zone and connect to the power supply, but too long may increase material costs. The connection between the cold end and the hot end is a stress concentration point, and gradual doping or welding technology (such as plasma welding) is required to make a smooth transition to reduce thermal stress and microcracks. The surface of the cold end is often coated with a conductive coating (such as an aluminized layer) to improve contact conductivity and prevent oxidation. Optimizing the cold end design also requires consideration of the heat dissipation environment, such as reducing the cold end temperature through a ceramic insulation sleeve or air convection to avoid overheating and deterioration of the connection point.

The coordinated optimization of the hot field and cold end structure needs to be combined with the furnace design and operating conditions. Thermal field simulation (such as finite element analysis) can predict the temperature distribution and guide the hot end layout and power allocation. The cold end heat dissipation design needs to match the furnace wall sealing and insulation materials (such as alumina fiber) to ensure the stability of the cold end temperature. The low-temperature brittleness of $MoSi_2$ (fracture toughness of about 2-3 $MPa\cdot m^{1/2}$) requires optimized design to avoid rapid thermal cycling through the "plague" range of 400-700°C to prevent the formation of non-protective oxides. Surface coatings (such as SiC, with a thermal expansion coefficient of about 4.5×10^{-6} K^{-1}) can enhance the oxidation resistance of the hot end and the corrosion resistance of the cold end. In practical applications, regular inspection of the thermal field uniformity and the cold end connection status, and adjustment of the heating and cooling rate (5-10°C/min) can ensure the long-term stability of the hot field and cold end structure, and meet high-demand applications such as semiconductor heat treatment and glass melting.

3.4 Electrical connection and support system design

The electrical connection and support system design of $MoSi_2$ heating elements are critical to their operational stability, heating efficiency and service life. The electrical connection system needs to ensure low-resistance contact between the cold end and the power supply to prevent local overheating and power loss. At the same time, the support system needs to provide mechanical support, allow thermal expansion, and reduce thermal stress and crack risks. The cold end resistivity of $MoSi_2$ (about 0.5×10^{-5} Ω· cm, at room temperature) is much lower than the hot end (2.0×10^{-5} Ω· cm), and the conductivity is optimized by aluminizing or doping with highly conductive materials (such as tungsten). Electrical connections usually use a highly conductive clamp (such as copper or aluminum alloy) to fix the cold end. The surface of the clamp needs to be plated with nickel or silver to prevent oxidation and ensure that the contact resistance is less than 0.01 Ω. Appropriate clamping force (usually 5-10 N/cm^2) needs to be applied to the connection point. Too tight may cause brittle fracture of $MoSi_2$ (fracture toughness is about 2-3 $MPa\cdot m^{1/2}$), and too loose may cause arcing or overheating.

The design of the electrical connection also needs to consider the type of power supply and the control system. $MoSi_2$ components are suitable for proportional control or phase-triggered power supplies and need to be equipped with a current limiting function (maximum current density ≤ 10 A/mm^2) to avoid non-proportional switching or "sudden" power supply damage to the components. Voltage regulators and transformers can stabilize the input (usually 20-100 V) and match the positive temperature coefficient resistivity change of $MoSi_2$ (about 4.5×10^{-5} at 1500°C) . Ω· cm). The cold end connection needs to be equipped with a heat dissipation device (such as air cooling or water cooling jacket) to keep the cold end temperature ≤400°C to prevent the connection point from deteriorating. The cable selection needs to be high temperature resistant (such as nickel-based alloy cable) and match the cold end size to avoid excessive contact resistance. To improve the connection reliability, conductive paste or aluminum foil gasket can be used to enhance the contact conductivity.

The support system design needs to ensure the mechanical stability and thermal expansion freedom of $MoSi_2$ elements. Common support materials are high-purity alumina or zirconium oxide (ZrO_2), which match the thermal expansion coefficient of $MoSi_2$ (8.1×10^{-6} K^{-1}) to reduce thermal stress. The support forms include clamps, suspension hooks and support beams. Vertical suspension is suitable for U-shaped and W-shaped elements, and horizontal support is suitable for straight rod elements. The support needs to be designed as a flexible structure to allow $MoSi_2$ to expand at high temperatures (about 0.8% linear expansion at 1500°C) to avoid stress concentration. The support surface needs to be smooth to prevent wear of the SiO_2 protective film on the surface of $MoSi_2$. The support system also needs to be coordinated with the furnace insulation material (such as alumina fiber) to ensure that the hot end is exposed to the heating zone and the cold end is located in the low temperature zone.

The coordinated design of the electrical connection and bracket system needs to consider the operating environment and the frequency of thermal cycles. Rapidly passing through the "plague" range of 400-700℃ can prevent the formation of non-protective oxides and protect the connection points and bracket surfaces. Regularly checking the contact status of the clamp, bracket wear and cold end temperature, cleaning the connection point oxides, and adjusting the clamping force can extend the life of the system. Surface coatings (such as SiC or Al_2O_3) can enhance the corrosion resistance of the cold end and the durability of the bracket. In actual applications, the electrical connection and bracket system needs to be customized according to the furnace type (such as tube furnace, box furnace) and application (such as ceramic sintering, metal heat treatment) to ensure the stable operation of the $MoSi_2$ heating element in a high temperature oxidizing atmosphere.

3.5 Terminal structure and connection method

The terminal structure and connection method of the molybdenum disilicide ($MoSi_2$) heating element have a key impact on its electrical performance, mechanical stability and service life. The terminal usually refers to the cold end part, which is responsible for connecting to the power system. It must ensure low resistance contact, high conductivity and high temperature corrosion resistance, while bearing thermal expansion and mechanical stress. The resistivity of the $MoSi_2$ cold end (about 0.5×10^{-5} at room temperature) Ω· cm) is significantly lower than the hot end (about 2.0×10^{-5} at room temperature) by doping with highly conductive materials. Ω· cm), and its diameter is usually 1.5-2 times that of the hot end (such as Φ6/12 or Φ9/18 specifications) to reduce heat generation and keep the cold end temperature below 400℃. The end structure design needs to optimize the transition zone between the cold end and the hot end to reduce stress concentration and prevent the initiation of microcracks, especially in the low-temperature brittle stage of $MoSi_2$ (fracture toughness is about 2-3 $MPa\cdot m^{1/2}$). Common end structures include straight, curved and tapered transition types. Straight cold ends are suitable for U-shaped and straight rod elements. Curved cold ends (such as 90° bends) are suitable for W-shaped or space-constrained furnaces. The tapered transition type smoothes the connection between the hot end and the cold end through a gradual diameter change to reduce thermal stress.

The connection methods mainly include clamping connection, welding connection and bolting connection. Clamping connection is the most common method. A high-conductivity clamp (such as copper or aluminum alloy, nickel or silver plated on the surface) is used to fix the cold end. The contact resistance needs to be controlled below 0.01 Ω. The clamping force needs to be moderate (5-10 N/cm²). Too tight may cause brittle fracture of $MoSi_2$, and too loose may cause arcing or local overheating. To enhance contact conductivity, an aluminized coating or conductive paste can be applied to the surface of the cold end. Welding connection connects the cold end to a conductive joint (such as nickel-based alloy) by plasma welding or resistance welding. It is suitable for high-precision applications, but the temperature needs to be controlled during the welding process to avoid deterioration of the hot end. Bolting connection is suitable for large industrial furnaces. The cold end is fixed with high-temperature resistant bolts and gaskets. It is easy to install but the contact resistance is slightly higher. It needs to be checked regularly for looseness. The connection method needs to match the power supply system. $MoSi_2$ components are recommended to use proportional control or phase-triggered power supplies with current limiting function (maximum current density ≤10 A/mm²) to avoid non-proportional switches from damaging components.

The optimization of the terminal structure and connection method needs to consider thermal cycling and environmental factors. Frequent thermal cycling may cause thermal stress accumulation at the cold end connection, causing microcracks or increased contact resistance, especially in the "plague" temperature range of 400-700°C, where non-protective oxides (mixtures of MoO_3 and SiO_2) may corrode the connection points. To improve durability, the cold end can be coated with a SiC or Al_2O_3 protective layer (the thermal expansion coefficient is approximately $4.5\times10^{-6}K^{-1}$ and $8\times10^{-6}K^{-1}$, respectively) to enhance oxidation resistance and corrosion resistance. Heat dissipation design (such as air cooling or ceramic insulation sleeves) can keep the cold end low and extend the life of the connection point. In practical applications, regularly checking the integrity of the clamp or solder joint, cleaning the oxide, and adjusting the clamping force can ensure the long-term stability of the terminal connection. The design of the end structure and connection method must also be coordinated with the furnace insulation material (such as alumina fiber) and the bracket system to ensure that the cold end is located in the low-temperature zone and meet the reliability requirements of high-temperature applications such as ceramic sintering and glass melting.

3.6 Key points of product customization design

The customized design of $MoSi_2$ heating elements is the key to meeting specific furnace types and process requirements, involving comprehensive optimization of structure, size, material modification and operating conditions. Customized design requires determining the shape, power density, temperature range and installation method of the element according to the application scenario (such as laboratory tube furnace, industrial ceramic sintering furnace, glass melting furnace or semiconductor heat treatment furnace) to achieve efficient heating, uniform temperature field and long life. The thermodynamic properties of $MoSi_2$ and its positive temperature coefficient resistivity provide flexibility for customized design, but its low-temperature brittleness requires that thermal stress and mechanical stability be fully considered in the design. The following are several key points for customized design.

First, the customization of structure and size needs to match the furnace geometry and heating requirements. U-shaped elements (hot end diameter 6-9 mm, length 100-500 mm) are suitable for centralized heating of small furnaces, W-shaped elements (hot end length 200-1000 mm) are suitable for uniform heating of large furnaces , spiral types are suitable for high heat density requirements of tubular furnaces, and straight rod types are suitable for long-distance linear heating. The diameter ratio of the hot end to the cold end (such as Φ6/12 or Φ9/18) needs to be optimized according to the power density, and the hot end length and spacing need to be simulated by thermal field (such as finite element analysis) to ensure temperature uniformity (±5°C). The cold end length (50-300 mm) needs to be sufficient to pass through the furnace wall and enter the low temperature zone. Special furnace types may require nonstandard shapes (such as L-shaped or multi-bend types), and the bending radius needs to be precisely controlled (usually ≥10 mm) to reduce thermal stress concentration.

Secondly, material modification and surface treatment are important links in customized design. The purity of $MoSi_2$ (≥99.5%) directly affects the oxidation resistance and thermal conductivity. High-purity raw materials can reduce the weakening of grain boundaries caused by impurities (such as Fe and Al). Doping modification (such as adding Y_2O_3 or Al_2O_3) can enhance the strength of grain boundaries and improve thermal shock resistance, which is suitable for frequent thermal cycle applications. Surface coatings (such as SiC or Al_2O_3) can extend the life of SiO_2 protective films and enhance the ability to resist "plague" oxidation. The coating thickness (10-50 μm) needs to be optimized according to the operating temperature and atmosphere. Too thick may cause peeling, and too thin will result in insufficient protection. The preparation process (such as hot pressing and sintering) needs to ensure density (close to 98%), reduce microscopic defects, and improve mechanical and thermodynamic properties.

Third, the customization of operating conditions needs to consider temperature, atmosphere, and thermal cycle frequency. The maximum operating temperature of $MoSi_2$ components can reach 1850°C in an oxidizing atmosphere, but it needs to be reduced to below 1500°C in a reducing or vacuum environment to prevent the SiO_2 film from failing. The customized design needs to clarify the atmosphere type (such as moisture content, impurity content). A high humidity environment may cause hydration of the SiO_2 film and reduce thermal conductivity. Applications with high thermal cycle frequencies (such as semiconductor heat treatment) need to optimize the heating and cooling rates (5-10°C/min) to avoid rapid passage through 400-700°C. The power control system needs to match the resistance characteristics of $MoSi_2$, use a proportional control power supply, and be equipped with a voltage regulator (20-100 V) and current limiting function to prevent overload.

Finally, the customized design for installation and maintenance needs to be coordinated with the furnace structure. Vertical suspension is suitable for U-shaped and W-shaped elements, horizontal support is suitable for straight rod type, and the bracket material (such as alumina, with a thermal expansion coefficient of about 8×10^{-6} K^{-1}) needs to match $MoSi_2$ to allow thermal expansion (about 0.8%, 1500°C). Electrical connections must use high-conductivity clamps or welded joints to ensure that the contact resistance is less than 0.01 Ω. The customized design should provide maintenance guidelines, including regular inspection of cold end temperature, SiO_2 film status and connection point integrity, and cleaning of furnace impurities (such as alkali metal oxides). Through thermal field simulation, material optimization and matching of operating conditions, customized designs can meet the performance requirements of specific applications and extend the service life of $MoSi_2$ heating elements in high temperature environments.

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$MoSi_2$ Heating Element Introduction

1. Overview of $MoSi_2$ Heating Element

Molybdenum disilicide ($MoSi_2$) heating elements are high-performance ceramic electric heating materials widely used in industrial furnace applications. In high-temperature oxidizing atmospheres, $MoSi_2$ forms a dense silica (SiO_2) protective layer on its surface, which effectively prevents further oxidation. It exhibits excellent oxidation resistance and thermal stability, allowing stable operation under high temperatures for extended periods.

2. Features of $MoSi_2$ Heating Element

Low thermal expansion coefficient: Well-matched with common ceramic substrates, minimizing the risk of cracking caused by thermal stress.

Excellent oxidation resistance: Forms a dense SiO_2 protective film on the surface, effectively preventing material degradation from oxidation.

Extremely high working temperature: Capable of continuous operation up to 1700°C, and a maximum usage temperature of 1800°C in oxidizing atmospheres.

Good high-temperature electrical resistance characteristics: $MoSi_2$ exhibits relatively stable resistivity at high temperatures, with only a gradual increase in resistivity at elevated temperatures.

3. Specifications of $MoSi_2$ Heating Element

Model (d1/d2)	Hot End Diameter (d1)	Cold End Diameter (d2)	Hot Zone Length (Le)	Cold Zone Length (Lu)	Common Types
φ3/6	3 mm	6 mm	100–300 mm	150–250 mm	Straight / U-type
φ4/9	4 mm	9 mm	100–500 mm	200–300 mm	Straight / U-type
φ6/12	6 mm	12 mm	100–600 mm	200–350 mm	Straight / U-type / W-type
φ9/18	9 mm	18 mm	150–800 mm	250–400 mm	Straight / U-type / W-type
φ12/24	12 mm	24 mm	200–1000 mm	300–500 mm	Straight / U-type / W-type

4. Typical Applications of $MoSi_2$ Heating Element

High-temperature sintering furnaces in the ceramics and powder metallurgy industries

Heat treatment equipment for steel and non-ferrous metals

High-temperature laboratory furnaces

Diffusion, annealing, and oxidation processes in the semiconductor and photovoltaic industries

5. Purchasing Information

Email: sales@chinatungsten.com; Phone: +86 592 5129595; 592 5129696

Website: www.molybdenum.com.cn

Chapter 4 Manufacturing Process of $MoSi_2$ Heating Element

4.1 Raw material selection and proportioning principles

Molybdenum disilicide ($MoSi_2$) heating elements begins with the selection and proportion of raw materials, the quality of which directly affects the thermodynamic properties, oxidation resistance and service life of the elements. $MoSi_2$ is an intermetallic compound with the chemical formula $MoSi_2$. It needs to be synthesized from high-purity molybdenum (Mo) and silicon (Si) raw materials, usually prepared in powder form by powder metallurgy. The core principle of raw material selection is to ensure high purity (usually ≥99.5%) and low impurity content to reduce the risk of grain boundary weakening and non-protective oxidation. Molybdenum powder requires a purity of ≥99.9%, and the content of major impurities (such as Fe, Al, C) should be less than 0.01%, because Fe and Al may cause grain boundary corrosion and reduce thermal shock resistance; carbon impurities may generate carbides and affect resistivity. Silicon powder also needs to be of high purity (≥99.9%) to avoid non-metallic impurities such as oxygen and nitrogen that cause defects in the SiO_2 protective film. Particle size distribution is another key factor. The particle size of molybdenum powder and silicon powder is usually controlled at 1-10 μm. Particles that are too large may cause uneven sintering, while particles that are too small will increase the preparation cost.

The proportioning principle is based on the stoichiometric ratio of $MoSi_2$ (Mo:Si=1:2 molar ratio), and the theoretical mass ratio of molybdenum to silicon is about 2.55:1. To ensure complete reaction, the actual proportion may deviate slightly from the stoichiometric ratio, for example, the silicon content is increased by 0.5-1% to compensate for the volatilization loss during high-temperature sintering. Doping modification is an important means to optimize performance. Commonly used dopants include rare earth oxides (such as Y_2O_3 , La_2O_3 , added in an amount of 0.1-1 wt%) to enhance grain boundary strength and thermal shock resistance, or alumina to improve the stability of SiO_2 film . Dopants need to be of high purity (≥99.95%) to avoid the introduction of additional impurities. The proportioning process needs to be carried out in an inert atmosphere (such as argon) or a vacuum environment to prevent oxidation of the raw materials. Mixing uniformity is critical to the final performance. Planetary ball mills or V-type mixers are usually used for mixing, and the ball milling time and speed are controlled to avoid particle breakage or contamination.

The selection and proportion of raw materials also need to consider the preparation process and application requirements. For example, hot pressing sintering requires finer particles (1-5 μm) to improve density (close to 98%), while self-propagating high-temperature synthesis (SHS) can accept slightly larger particles (5-10 μm) to reduce costs. For high-precision applications (such as semiconductor heat treatment), ultra-high purity raw materials (≥99.99%) must be selected and the proportion accuracy (±0.1%) must be strictly controlled. The quality control process includes chemical composition analysis (such as ICP-MS) and particle size distribution detection (such as laser particle size analyzer) to ensure that the raw materials meet the design requirements. Reasonable raw material selection and proportioning lay the foundation for subsequent molding and sintering, ensuring the stability and reliability of $MoSi_2$ heating elements in high-temperature oxidizing atmospheres.

4.2 Powder Metallurgy and Isostatic Pressing Process

Powder metallurgy is the core process for manufacturing $MoSi_2$ heating elements. Combined with isostatic pressing, it can produce high-density and high-performance elements, suitable for U-shaped, W-shaped, straight rod-shaped and spiral-shaped structures. The powder metallurgy process includes four main steps: raw material mixing, molding, sintering and post-processing. Among them, isostatic pressing is the key molding technology, which can ensure the dimensional accuracy and microstructural uniformity of the elements. The thermal conductivity (about 15 W/(m·K) at 1500°C), thermal expansion coefficient (about 8.1×10^{-6} K^{-1}) and oxidation resistance of $MoSi_2$ depend on high density (≥98%) and low defect rate. The combination of powder metallurgy and isostatic pressing can effectively meet these requirements.

Raw material mixing : The mixing process uniformly mixes high-purity molybdenum powder and silicon powder in a stoichiometric ratio (Mo:Si=1:2) or a slightly silicon-rich ratio (silicon increased by 0.5-1%), usually using a planetary ball mill or V-type mixer in an inert atmosphere (such as argon) or a vacuum environment. The ball milling medium is high-purity alumina or zirconia, the ball-to-material ratio is controlled at 2:1 to 5:1, and the mixing time is 4-8 hours to ensure that the particles are evenly dispersed without introducing contamination. Dopants (such as Y_2O_3 , Al_2O_3 , added in an amount of 0.1-2 wt%) are added during the mixing stage , and their particle size needs to be controlled to ensure uniform distribution. The mixed powder is sieved to remove agglomerated particles and dried to remove moisture.

Isostatic pressing : Isostatic pressing (cold isostatic pressing, CIP) is the main technology for forming $MoSi_2$ heating elements. The mixed powder is pressed into the desired shape (such as U-shaped, W-shaped or straight rod-shaped green body) by applying uniform pressure in a liquid medium (such as water or oil). The advantages of isostatic pressing are uniform pressure and high green body density, which can reduce uneven shrinkage during subsequent sintering. The molding mold is usually made of flexible rubber or polyurethane material, which is pressure-resistant and has no chemical reaction with $MoSi_2$ powder. The process parameters include pressure, holding time and powder filling uniformity, and it is necessary to ensure that the green body is free of cracks or delamination. Complex shapes (such as spirals) may require segmented molding or combined with preforming technology. In order to improve the strength of the green body, a small amount of organic binder can be added, which is removed in the subsequent pre-sintering.

Sintering process : Sintering is a key step in powder metallurgy, which enables the $MoSi_2$ green body to reach high density and form a stable tetragonal α-type crystal structure. Common sintering methods include hot pressing sintering (HP) and pressureless sintering. Hot pressing sintering is more suitable for high-performance $MoSi_2$ heating elements. Hot pressing sintering is carried out in a vacuum or inert atmosphere (argon), with a temperature controlled at 1600-1800°C, a pressure of 20-40 MPa, and a holding time of 1-3 hours. During the sintering process, molybdenum reacts with silicon to form $MoSi_2$, while dopants (such as Y_2O_3) promote grain boundary bonding and reduce porosity. The sintering temperature needs to be precisely controlled. Too high a temperature may cause Si volatilization and reduce the quality of the SiO_2 film ; too low a temperature may result in insufficient density, affecting thermal conductivity and thermal shock resistance. Pressureless sintering is suitable for cost-sensitive applications, with a temperature of 1700-1900°C, but the density is low, which may increase the risk of microcracks.

Post-processing : Sintered $MoSi_2$ components require post-processing, including surface polishing, dimensional trimming and application of protective coatings. Surface polishing (using a diamond wheel) removes surface defects and reduces the risk of thermal stress concentration. Dimensional trimming ensures that the components meet the design specifications. Protective coatings are applied by plasma spraying or chemical vapor deposition (CVD) to enhance oxidation resistance and resistance to "plague" oxidation. Quality inspection links include density testing (Archimedes method), microstructure analysis (SEM) and resistivity measurement to ensure that component performance meets the application requirements of ceramic sintering, glass melting, etc.

The optimization of powder metallurgy and isostatic pressing processes requires a comprehensive consideration of cost and performance. Hot pressing combined with isostatic pressing can produce high-density components, suitable for high-precision applications (such as semiconductor heat treatment); pressureless sintering is low-cost and suitable for large-scale industrial furnaces. Process control needs to avoid the "plague" temperature range of 400-700°C to prevent the formation of non-protective oxides. Regularly test the purity of raw materials, green body quality and sintering parameters to ensure the stability and reliability of $MoSi_2$ heating elements in high-temperature oxidizing atmospheres.

4.3 High temperature sintering and post-processing technology

High temperature sintering is the core process in the manufacture of molybdenum disilicide ($MoSi_2$) heating elements. It aims to transform the formed green body into a component with high density (≥98% theoretical density), excellent mechanical properties and a stable tetragonal α-type crystal structure, ensuring that its thermal conductivity, oxidation resistance and thermal shock resistance meet the requirements of high temperature applications. The sintering process is usually carried out in a vacuum or inert atmosphere (such as argon) to prevent oxidation. Common methods include hot pressing sintering (HP), pressureless sintering and self-propagating high temperature synthesis (SHS). Hot pressing sintering is the mainstream process for high-performance $MoSi_2$ components. The temperature is controlled at 1600-1800°C, the pressure is 20-40 MPa, and the holding time is 1-3 hours. The high temperature allows molybdenum to fully react with silicon to form $MoSi_2$, while the dopant promotes grain boundary bonding and reduces porosity. The sintering temperature needs to be precisely controlled. If it is too high, Si may volatilize and weaken the quality of the surface SiO_2 protective film; if it is too low, the density will be insufficient (<95%), reducing thermal conductivity and thermal shock resistance.

Post-processing technology is crucial to the performance optimization of $MoSi_2$ components, including surface polishing, dimensional trimming and performance testing. Surface polishing uses diamond grinding wheels or alumina abrasives to remove surface defects (such as micropores and sintering nodules) formed during sintering, reduce thermal stress concentration, and enhance thermal shock

电话/TEL：0086 592 512 9696
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sales@chinatungsten.com

resistance. Dimensional trimming ensures that the components meet the design specifications through precision machining (such as CNC cutting) to meet the accuracy requirements of structures such as U-shaped, W-shaped or spiral shapes. Performance testing includes density testing (Archimedes method, target ≥98%), microstructure analysis and resistivity measurement to ensure the consistency of electrical and thermal performance of components. Pre-oxidation treatment can generate a dense SiO_2 protective film on the surface to enhance oxidation resistance and anti-"plague" oxidation ability. Post-processing also needs to be carried out in an inert atmosphere, avoiding the temperature range of 400-700°C to prevent the generation of non-protective oxides (mixture of MoO_3 and SiO_2). High-quality post-processing can significantly improve the stability and life of $MoSi_2$ components in high-temperature oxidizing atmospheres, meeting the needs of high-precision applications such as semiconductor heat treatment.

4.4 Surface protection layer technology

Surface protection layer technology is an important part of the manufacturing of $MoSi_2$ heating elements. By applying a protective coating, the oxidation resistance, thermal shock resistance and corrosion resistance are enhanced, and the service life of the element in a high-temperature oxidizing atmosphere is extended. $MoSi_2$ naturally forms a SiO_2 protective film above 800°C , but at extreme temperatures or frequent thermal cycles, the SiO_2 film may become thinner due to the volatilization of Si or MoO_3 , especially in the "plague" temperature range of 400-700°C, which is prone to powdering. The surface protection layer makes up for the shortcomings of the SiO_2 film by applying an oxide coating (such as Al_2O_3 , ZrO_2), a carbide coating (such as SiC) or a composite coating (such as Al_2O_3 -SiC) . Al_2O_3 coating (melting point about 2050°C) is applied by plasma spraying or chemical vapor deposition (CVD) with a thickness of 10-50 μm . It has high oxidation resistance and low oxygen diffusion coefficient, and is suitable for ceramic sintering furnaces. SiC coating is applied by reaction sintering or CVD with a thickness of 20-100 μm. It has enhanced thermal shock resistance and wear resistance and is suitable for glass melting furnaces. Composite coatings combine the advantages of multiple materials, such as Al_2O_3 - SiC coatings , which have both high oxidation resistance and thermal shock resistance and are suitable for complex working conditions.

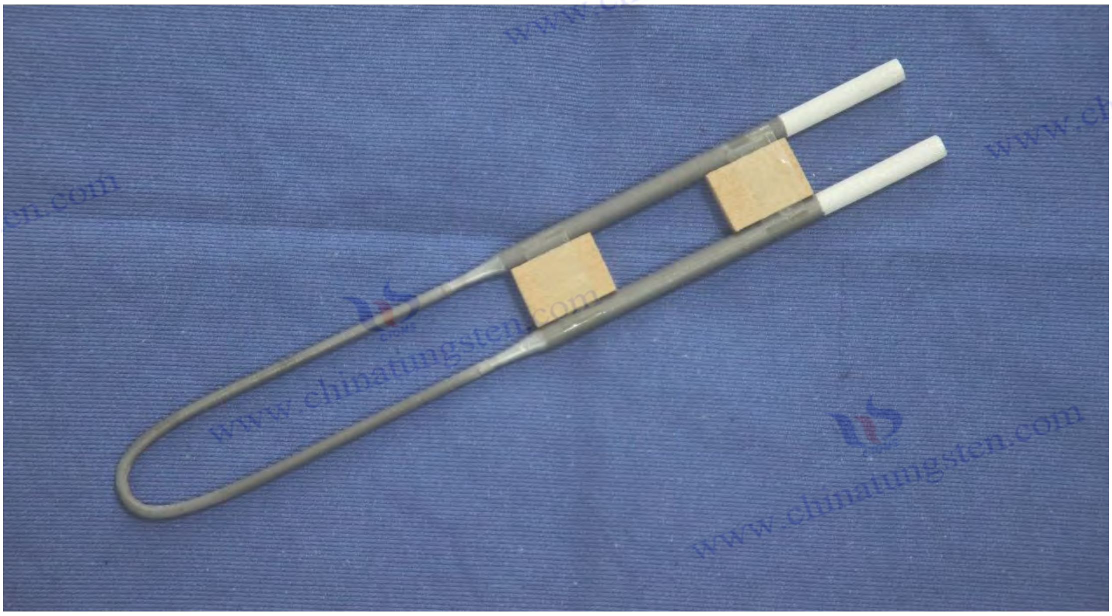
The coating application process has a significant impact on performance. Plasma spraying can form thick and dense coatings, which are suitable for industrial-scale production, but there may be micropores, which slightly reduce thermal conductivity. The CVD process produces uniform, thin coatings (10-30 μm) with high adhesion and low thermal stress, which are suitable for high-precision applications, but the cost is relatively high. The coating thickness needs to be precisely controlled. Too thick may cause peeling due to thermal expansion mismatch, and too thin may provide insufficient protection. Interface design (such as adding a SiC transition layer) can improve the bonding between the coating and the $MoSi_2$ substrate and reduce thermal stress. The coating must also withstand high humidity or corrosive atmospheres (such as sulfur-containing gases). Al_2O_3 coatings may hydrate in high humidity environments, and process parameters need to be optimized. Quality inspections include coating thickness measurement (ultrasonic or SEM), adhesion testing (scratch method) and oxidation resistance testing to ensure coating performance. The optimization of surface protection layer technology needs to be combined with the application environment. Semiconductor heat treatment furnaces require high-purity CVD coatings to avoid contamination, and glass melting furnaces prefer thick SiC coatings to enhance thermal shock resistance. Regularly checking the integrity of the coating and quickly passing through the 400-700℃ temperature range can prevent "plague" oxidation and coating degradation. In the future, nanostructured coatings and multi-layer composite coatings are expected to further improve the surface performance of $MoSi_2$ components to meet more demanding high-temperature application requirements.

4.5 Welding and end processing technology

Welding and end processing technology is the final stage of $MoSi_2$ heating element manufacturing, which aims to ensure the stability and electrothermal performance of the cold end connection to the power supply, while optimizing the end structure to withstand mechanical and thermal stress. The $MoSi_2$ cold end is doped with highly conductive materials (such as aluminum or tungsten) to reduce resistivity. The diameter is 1.5-2 times that of the hot end and needs to be kept low to prevent overheating degradation. Welding technology is used to connect the cold end to the conductive joint (such as nickel-based alloy or copper alloy), ensuring low contact resistance ($<0.01\ \Omega$) and high mechanical strength. Common welding methods include plasma welding and resistance welding. Plasma welding is carried out in an inert atmosphere (such as argon) and the temperature is controlled at 1200-1400℃. It can form a uniform and high-strength weld, which is suitable for high-precision applications (such as semiconductor heat treatment). Resistance welding uses high current to quickly heat the cold end and the joint. It is low in cost but the weld uniformity is slightly inferior, which is suitable for industrial furnaces. During the welding process, excessive temperatures must be avoided to prevent degradation of the $MoSi_2$ crystal structure at the hot end or damage to the SiO_2 film .

The end processing technology includes cold end surface treatment, dimensional trimming and conductive coating application. The cold end surface is mechanically polished to remove oxide layers and defects to improve the contact quality with the clamp or weld. Dimensional trimming uses CNC machining or diamond cutting to ensure that the diameter and length of the cold end meet the design tolerance and are suitable for U-shaped, W-shaped or straight rod components. Conductive coatings (such as aluminized layers, 5-20 μm thick) are applied by electroplating or thermal spraying to enhance the conductivity of the cold end, reduce contact resistance, and prevent oxidation corrosion. End processing also needs to optimize the transition zone between the hot end and the cold end, using conical transition or gradient doping technology to smooth the thermal stress distribution and reduce the risk of microcracks ($MoSi_2$ fracture toughness is about 2-3 $MPa \cdot m^{1/2}$). The processing process needs to be carried out in an inert atmosphere to avoid the "plague" temperature range of 400-700℃ and prevent the formation of non-protective oxides.

Optimization of welding and end processing needs to take into account operating conditions and installation methods. Frequent thermal cycles may cause stress concentration in the weld or end, and the weld integrity and cold end temperature need to be checked regularly. Protective coatings (such as SiC or Al_2O_3 , thickness 10-50 μm) can be applied to the cold end to enhance corrosion resistance and thermal shock resistance. Quality inspection includes weld strength testing (tensile or shear test), contact resistance measurement and microstructure analysis (SEM) to ensure end performance. In practical applications, welding and end processing need to be coordinated with electrical connection systems (such as copper clamps) and bracket design (alumina support) to ensure the long-term stability of $MoSi_2$ heating elements in high temperature oxidizing atmospheres to meet the application requirements of ceramic sintering, glass melting, etc.



CTIA GROUP LTD Molybdenum Silicate Rod

Chapter 5 Performance Test of $MoSi_2$ Heating Element

5.1 Resistivity and temperature relationship test

Resistivity is a key electrothermal performance parameter of molybdenum disilicide ($MoSi_2$) heating elements, which directly affects their heating efficiency, power output and temperature control accuracy. $MoSi_2$ has a positive temperature coefficient (PTC) resistivity characteristic, and the resistivity increases with increasing temperature, which enables it to adaptively adjust power at high temperatures and is suitable for high-temperature applications such as ceramic sintering and glass melting (up to 1800-1850°C). The test of the relationship between resistivity and temperature is intended to quantify the resistance characteristics of $MoSi_2$ at different temperatures, verify its electrothermal stability and provide data for component design and operation parameter optimization. The test is usually carried out in a laboratory or industrial furnace, using a high-precision resistance tester (such as the four-probe method) and a temperature-controlled furnace to ensure data reliability.

The test method includes placing a $MoSi_2$ heating element (such as U-type, W-type, common specifications Φ6/12 or Φ9/18) in a controlled oxidizing atmosphere furnace, gradually increasing the temperature, and measuring the resistivity in the range of room temperature (25°C) to 1800°C. The test equipment includes a high-precision DC power supply (constant current or constant voltage mode, current density ≤10 A/mm²), a digital multimeter (accuracy ±0.1%), and a thermocouple (K type or S type, accuracy ±1°C). During the test, it is necessary to quickly pass through the "plague" temperature range of 400-700°C to avoid the generation of non-protective oxides (a mixture of MoO_3 and SiO_2) that affect the resistivity. The resistivity (ρ) is calculated by the formula $\rho = R \cdot A/L$, where R is the measured resistance, A is the hot end cross-sectional area, and L is the hot end length. The test environment maintains an oxidizing atmosphere and the humidity is less than 30% to ensure the stability of the surface SiO_2 protective film.

$MoSi_2$ is about 2.0×10^{-5} at room temperature . Ω· cm, which increases significantly with increasing temperature and is approximately 4.0×10^{-5} at 1000°C Ω· cm, about 4.5×10^{-5} at 1500°C Ω· cm, up to 4.8×10^{-5} at 1800°C Ω· cm. This positive temperature coefficient characteristic makes the $MoSi_2$ element have stable power output at high temperatures, but it also means that the cold end (doped with aluminum or tungsten, with a resistivity of about 0.5×10^{-5} Ω· cm) needs to be kept low to avoid overheating. Test results show that the change of resistivity with temperature is affected by the purity and microstructure of the material. The resistivity curve of high-purity $MoSi_2$ is more stable, and the resistivity fluctuation of high-density components is small. Doping modification can further stabilize the resistivity and reduce grain boundary scattering. The test also needs to record the effect of thermal cycling on resistivity. After multiple thermal cycles, the resistivity may increase slightly, and long-term stability needs to be evaluated.

Test precautions include calibrating equipment accuracy, ensuring stable cold-end connections (contact resistance < 0.01 Ω), and avoiding reducing or high-humidity atmospheres (humidity > 70% may cause SiO_2 film hydration). Test data is analyzed by fitting resistivity-temperature curves (such as quadratic

电话/TEL：0086 592 512 9696
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sales@chinatungsten.com

polynomials) to optimize component design and power control systems. In practical applications, resistivity test results guide the operating parameters of $MoSi_2$ components to ensure electrothermal performance and temperature control accuracy in high-temperature oxidizing atmospheres.

5.2 Test on the relationship between high temperature service life and thermal shock performance

High temperature service life and thermal shock performance are key performance indicators of $MoSi_2$ heating elements, which determine their reliability and durability in high temperature oxidizing atmospheres (up to 1800-1850°C). High temperature service life refers to the time that the element can operate continuously at the target temperature without significant performance degradation (such as resistivity drift, microcrack propagation, or SiO_2 film failure), and thermal shock performance refers to the element's ability to resist cracking under rapid temperature changes (such as thermal cycling or rapid cooling and heating). $MoSi_2$'s low-temperature brittleness and "plague" oxidation make it vulnerable to damage in thermal cycles. Testing the relationship between high temperature service life and thermal shock performance is intended to evaluate the durability of the element under actual working conditions (such as ceramic sintering, metal heat treatment) and provide a basis for optimizing materials and designs. Test methods include long-term high temperature operation tests and thermal shock cycle tests. The long-term high-temperature operation test is carried out in an oxidizing atmosphere furnace. The $MoSi_2$ element (such as U-type or W-type, Φ6/12 or Φ9/18) is placed at the target temperature, the power density is controlled at 15-20 W/cm², and it is continuously operated for 1000-5000 hours , and the resistivity change, surface SiO_2 film state and microstructure evolution are recorded. The test equipment includes a high-temperature furnace (accuracy ±5°C), a resistance tester (four-probe method, accuracy ±0.1%) and a microscope (SEM, analysis of cracks and film layers). The thermal shock cycle test simulates rapid heating and cooling. Typical conditions are 25-1500°C cycles, heating and cooling rates of 10-20°C/min, cycles of 100-1000 times, and rapid passage through 400-700°C to avoid "plague" oxidation. After testing, the number of cracks (optical microscope, magnification 50-200×), SiO_2 film thickness and mechanical strength changes (three-point bending test, fracture strength about 200-300 MPa) were evaluated.

Test results show that the service life of $MoSi_2$ components can reach more than 5000 hours at 1500°C and about 1000-2000 hours at 1800°C. The service life is affected by the stability of the SiO_2 film. At high temperatures, Si volatilization and MoO_3 volatilization may cause the film layer to become thinner (<5 μm), reduce oxidation resistance, and increase the resistivity by 10-20%, which may cause performance degradation. High-purity $MoSi_2$ (≥99.5%) and hot-pressed sintered components (density ≥98%) have a longer service life because impurities (such as Fe, Al) and pores reduce grain boundary weakening and crack initiation. Doping modification (such as Y_2O_3 , 0.1-1 wt%) can enhance grain boundary strength and extend the service life by 10-20%. In terms of thermal shock resistance, microcracks after thermal cycling mainly appear at the hot-end-cold-end connection. W-type components have better thermal shock resistance than U-type components due to their multi-hot-end design, and straight rod components have better crack resistance due to their linear structure. Surface coating can significantly improve thermal shock resistance, reduce crack propagation (crack density reduced by 30-50%) and SiO_2 film peeling. Test precautions include maintaining an oxidizing atmosphere, avoiding high humidity (humidity > 70%) and reducing environments (causing SiO_2 film failure), and regularly calibrating thermocouples and resistance testers. Test data guides material optimization (such as doping) and structural design (such as optimizing bending radius) of $MoSi_2$ components through life prediction models (such as Arrhenius model) and crack statistical analysis. In practical applications, test results are used to formulate maintenance plans (such as regular inspections of cracks and film layers) and operating parameters to ensure the long-term reliability and thermal shock stability of $MoSi_2$ heating elements in high-temperature furnaces.

5.3 Stability test in oxidative environment

Stability testing in an oxidizing environment is the key to evaluating the long-term performance of molybdenum disilicide ($MoSi_2$) heating elements in a high-temperature oxidizing atmosphere (up to 1800-1850°C), focusing on the formation and retention of the SiO_2 protective film on its surface, its antioxidant properties, and the stability of its microstructure. $MoSi_2$ achieves excellent oxidation resistance in an oxidizing atmosphere by forming a dense SiO_2 protective film on its surface, but volatilization of Si or MoO_3 at high temperatures may cause the film layer to become thinner, especially in the "plague" temperature range of 400-700°C, where non-protective oxidation is prone to occur, generating a mixture of MoO_3 and SiO_2 , resulting in material pulverization. The stability test is designed to quantify the life, resistivity change, and surface state of $MoSi_2$ elements in an oxidizing environment, and to provide reliable data for high-temperature applications such as ceramic sintering and glass melting.

The test methods include long-term oxidation exposure test and cyclic oxidation test. The long-term oxidation exposure test places the $MoSi_2$ element (such as U-type, W-type, Φ6/12 or Φ9/18) in a high-temperature oxidation atmosphere furnace, the temperature is controlled at 1500-1800℃, the power density is 15-20 W/cm², and it runs continuously for 1000-5000 hours. The test equipment includes a high-temperature furnace, a resistance tester (four-probe method, accuracy ±0.1%), a scanning electron microscope (SEM) and an X-ray diffractometer (XRD) to analyze the SiO_2 film thickness (target 10-20 μm), surface morphology and phase composition. The cyclic oxidation test simulates the thermal cycle in actual working conditions, with conditions of 25-1500℃ or 25-1800℃, a heating and cooling rate of 5-10℃/min, a cycle number of 100-1000 times, and a rapid passage through 400-700℃ to avoid "plague" oxidation. After testing, resistivity changes, SiO_2 film integrity, number of cracks, and mass loss were evaluated.

Test results show that $MoSi_2$ components have high stability in an oxidizing atmosphere at 1500℃ , with a lifespan of more than 5000 hours, the SiO_2 film remains dense (thickness 10-15 μm), and the resistivity increase is less than 10%. High-purity $MoSi_2$ and hot-pressed sintered components (density ≥ 98%) have better stability, fewer film defects, and a mass loss rate of less than 0.5 mg/cm²/1000h. Doping modification (such as Y_2O_3 , 0.1-1 wt%) can enhance the adhesion of the SiO_2 film and reduce peeling. Cyclic oxidation tests show that thermal shock cracks mainly appear at the hot-end-cold-end connection, and the W-type component is slightly better than the U-type due to its multi-hot-end design. Surface coatings (such as SiC or Al_2O_3 , thickness 10-50 μm) can significantly improve stability and reduce mass loss by 30-50%. The test should avoid high humidity (humidity>70%) or sulfur-containing atmosphere to prevent hydration or corrosion of the SiO_2 film .

5.4 Hardness test of heating element

Hardness testing is an important means of evaluating the mechanical properties of $MoSi_2$ heating elements, which directly reflects their resistance to wear, mechanical stress and thermal shock crack growth. As an intermetallic compound, $MoSi_2$ has a high hardness, but its low-temperature brittleness makes it easy to produce microcracks during mechanical shock or thermal cycling. The hardness test is designed to quantify the surface hardness and microstructural strength of $MoSi_2$ components, providing a basis for optimizing manufacturing processes (such as hot pressing sintering) and doping modification, and meeting the mechanical stability requirements of applications such as ceramic sintering and metal heat treatment.

The test method adopts the Vickers Hardness Test. A Vickers hardness tester is used to apply indentation on the surface of the $MoSi_2$ element (hot end and cold end), and the diagonal length of the indentation is measured (accuracy ±0.1 μm) to calculate the hardness value. The test is carried out at room temperature, and the sample surface must be clean to avoid the influence of oxide layer or impurities. The high temperature hardness test uses a high temperature hardness tester to simulate the actual operating conditions. It must be carried out in an inert atmosphere (such as argon) to prevent oxidation. To evaluate the hardness uniformity, the test points cover the hot end, cold end and hot end-cold end transition zone, with at least 5 points in each area, and the average value is taken (deviation <5%). Auxiliary tests include microstructural analysis and crack propagation evaluation.

Test results show that the room temperature Vickers hardness of $MoSi_2$ components is 8-10 GPa, which drops to about 4-6 GPa at 1500°C due to grain boundary sliding and softening effects at high temperatures. High-purity $MoSi_2$ and hot-pressed sintered components (density ≥ 98%) have higher hardness (close to 10 GPa) due to low porosity (<2%) and fewer grain boundary defects. Doping modification (such as Y_2O_3 or Al_2O_3, 0.1-2 wt%) can increase the hardness by 5-10% because rare earth oxides enhance the bonding force of grain boundaries. The hardness of the cold end is slightly lower than that of the hot end (about 7-9 GPa) because doping with aluminum or tungsten reduces the strength of the crystal. The hardness may drop by 5-15% after thermal cycling due to the accumulation of microcracks. Surface coatings can significantly improve surface wear resistance, but coating peeling may expose the substrate. The test requires controlled indentation depth (<10% sample thickness) to avoid matrix effects, and the results are used to evaluate the mechanical durability of components during installation, operation and maintenance.

5.5 Test on the relationship between oxidation resistance and temperature

The oxidation resistance and temperature relationship test is the core of the $MoSi_2$ heating element performance test, which aims to evaluate its oxidation behavior at different temperatures, the formation and stability of the SiO_2 protective film, as well as the material mass loss and resistivity change, to provide reliable data for high-temperature applications (such as glass melting and semiconductor heat treatment). The oxidation resistance of $MoSi_2$ depends on the surface SiO_2 protective film, which forms a dense film layer above 800°C, but is prone to generate non-protective oxides in the "plague" temperature range of 400-700°C, resulting in powdering; at nearly 1850°C, Si volatilization may cause the film layer to become thinner. The test is designed to quantify the change of oxidation resistance with temperature and optimize the operating temperature and maintenance strategy.

The test methods include constant temperature oxidation test and variable temperature oxidation test. The constant temperature oxidation test places the $MoSi_2$ element (such as U-type, W-type, Φ6/12 or Φ9/18) in an oxidizing atmosphere furnace with a temperature range of 400-1800°C, a running time of 100-1000 hours, and a power density of 15-20 W/cm². The test equipment includes a high temperature furnace (accuracy ±5°C), a precision balance (accuracy ±0.1 mg), SEM and XRD to measure the mass loss rate (mg/cm²/h), SiO_2 film thickness and phase composition. The variable temperature oxidation test simulates thermal cycling with conditions of 25-1500°C or 25-1800°C, a heating and cooling rate of 5-10°C/min, 50-500 cycles, and rapid passage through 400-700°C. After testing, the resistivity change (four-probe method, accuracy ±0.1%), film integrity (SEM) and crack density (optical microscope, magnification 50-200×) were evaluated.

Test results show that $MoSi_2$ has the best oxidation resistance at 800-1500°C, the SiO_2 film thickness is stable, the mass loss rate is less than 0.2 mg/cm²/1000h, and the resistivity increase is less than 10%. At 400-700°C, non-protective oxidation causes the mass loss rate to be as high as 1-2 mg/cm²/100h, and the resistivity increases by 20-30%, and it is necessary to pass through this range quickly. At 1800°C, Si volatilization intensifies, the SiO_2 film becomes thinner, the mass loss rate increases to 0.5-1 mg/cm²/1000h, and the life is shortened to 1000-2000 hours. High-purity $MoSi_2$ and hot-pressed sintered components (density ≥98%) have stronger oxidation resistance and fewer film defects. Doping modification enhances film adhesion and reduces the mass loss rate by 20-30%. Surface coating significantly improves oxidation resistance, especially at 1800°C, where the mass loss rate is reduced by 40-60%. The test should avoid high humidity or reducing atmosphere to ensure data reliability. The results are used to guide the optimization of operating temperature (recommended 1500-1700°C) and maintenance plan (such as regular inspection of the membrane layer) through oxidation kinetic analysis (such as parabolic model).

5.6 Relationship between rod surface roughness and resistivity

Surface roughness is an important factor affecting the electrothermal performance of molybdenum disilicide ($MoSi_2$) heating elements, and is directly related to the uniformity of its resistivity and current distribution. The surface roughness of $MoSi_2$ components is mainly determined by the manufacturing process (such as hot pressing and isostatic pressing) and subsequent processing (such as polishing and sandblasting). Surfaces with high roughness may lead to local current concentration, uneven thermal stress, and uneven formation of SiO_2 protective film, thereby affecting the resistivity stability. Testing the relationship between surface roughness and resistivity aims to quantify the impact of surface morphology on electrothermal performance, provide a basis for optimizing manufacturing processes and component design, and is particularly suitable for high-precision temperature control scenarios such as ceramic sintering and glass melting. The test method uses a surface roughness meter (such as a profilometer or atomic force microscope, with an accuracy of ±0.01 μm) to measure the surface roughness parameters (such as Ra, Rz) of the $MoSi_2$ rod. The test area covers the hot end and the cold end, and the sample surface needs to be clean to avoid interference from impurities. The resistivity test uses a four-probe method (accuracy ±0.1%), measured in the range of room temperature to 1800°C, combined with samples of different roughness. The test environment is an oxidizing atmosphere, and the 400-700°C "plague" temperature range is quickly passed to avoid the formation of non-protective oxides. The resistivity (ρ) is calculated by the formula $\rho = R \cdot A/L$, where R is the measured resistance, A is the cross-sectional area, and L is the test length. The test needs to record the effect of surface roughness on the formation of SiO_2 film (SEM observation, magnification 50-200×) and the uniformity of current distribution (infrared thermometer, accuracy ±1°C).

the resistivity of $MoSi_2$ rods with lower surface roughness is more stable and has a smaller fluctuation range, because the smooth surface reduces local current concentration and thermal stress accumulation. High-roughness surfaces may lead to local increases in resistivity because surface defects increase grain boundary scattering and uneven current paths. The polished $MoSi_2$ element has a more uniform SiO_2 film (thickness 10-15 μm) at high temperatures , with less resistivity variation, which is suitable for high-precision applications. Sandblasted or rough surfaces are prone to microcracks during thermal cycles, which increases resistivity fluctuations and affects long-term stability. The test requires calibration of equipment accuracy, control of cold end connections and atmosphere conditions, and avoidance of high humidity (humidity > 70%) causing hydration of the SiO_2 film . The data is analyzed by fitting the roughness-resistivity curve and used to optimize the surface treatment process (such as chemical polishing or plasma spraying) to improve the electrothermal performance and temperature control accuracy of $MoSi_2$ elements .

5.7 Effect of rod coating uniformity on service life

The surface coating of $MoSi_2$ heating elements (such as SiC, Al_2O_3 , thickness 10-50 μm) is the key to improving thermal shock resistance and corrosion resistance. The uniformity of the coating directly affects the stability of the SiO_2 protective film, the oxidation rate and the service life of the element. Uneven coating may lead to insufficient local oxidation resistance, thermal stress concentration or peeling, and shorten the operating time of the element in a high-temperature oxidation environment (such as ceramic sintering, semiconductor manufacturing). Testing the effect of coating uniformity on service life aims to evaluate the effect of coating quality on component durability and provide data support for optimizing coating processes (such as chemical vapor deposition and plasma spraying).

The test methods include coating uniformity detection and high temperature life test. Coating uniformity is analyzed by scanning electron microscopy (SEM, accuracy ±0.1 μm) and X-ray spectrometer (EDS), measuring coating thickness distribution and composition uniformity (Si/C ratio in SiC or Al/O ratio in Al_2O_3). Samples include $MoSi_2$ rods with different coating processes (such as CVD coating, spray coating), and the test area covers the hot end and cold end transition zone. High temperature life test is carried out in an oxidizing atmosphere furnace with a temperature range of 1500-1800°C, a power density of 15-20 W/cm², a running time of 1000-5000 hours, and a rapid passage of 400-700°C to avoid "blight" oxidation. The test records the mass loss rate (precision balance, accuracy ±0.1 mg), SiO_2 film state (SEM observation) and resistivity change (four-probe method, accuracy ±0.1%). Auxiliary tests include coating adhesion and thermal shock resistance.

$MoSi_2$ components with high coating uniformity (thickness deviation <5%) is significantly extended, because the uniform coating promotes the stable formation of SiO_2 film and reduces local oxidation and peeling. CVD coatings show longer life at 1800°C due to their high density and adhesion, making them suitable for high-demand applications. If the spray coating has uneven thickness (deviation >10%), it may peel off in the hot-end-cold-end transition zone, causing the SiO_2 film to become thinner, accelerating oxidation degradation, and shortening its life. Uniform coatings also reduce the density of microcracks in thermal cycles and improve thermal shock resistance. The test requires control of the atmosphere and the heating and cooling rates to avoid high humidity or reducing environments (which cause the SiO_2 film to fail). The data guides coating process optimization and maintenance strategies (such as regular inspection of coating integrity) through coating thickness-life relationship analysis to ensure the long-term reliability of $MoSi_2$ components in high-temperature oxidizing environments.

5.8 Relationship between service life and stress coupling

$MoSi_2$ heating elements is affected by the coupling of thermal stress, mechanical stress and environmental stress, especially in high-temperature oxidizing atmospheres and frequent thermal cycles. Thermal stress comes from the temperature gradient caused by rapid heating and cooling, mechanical stress comes from installation or operation vibration, and environmental stress is related to oxidizing or corrosive atmospheres. Stress coupling may cause microcrack propagation, SiO_2 film peeling or resistivity drift, thereby shortening the life of the element. Testing the relationship between service life and stress coupling aims to quantify the impact of stress on the durability of $MoSi_2$ elements, provide a basis for optimizing design (such as shape, bracket) and operating parameters (such as heating and cooling rate), and is suitable for high-temperature applications such as ceramic sintering and glass processing.

The test methods include stress simulation and life test. Stress simulation uses finite element analysis (FEA) to evaluate the thermal stress distribution in the hot-cold transition zone (based on the thermal expansion coefficient and thermal conductivity of $MoSi_2$), combined with mechanical stress testing (three-point bending test, accuracy ±0.1 MPa). The life test is carried out in an oxidizing atmosphere furnace, with a temperature of 1500-1800°C, a power density of 15-20 W/cm², an operation time of 1000-5000 hours, and thermal cycle conditions of 25-1500°C. The test samples include U-shaped and W-shaped $MoSi_2$ elements (Φ6/12 or Φ9/18), and some surface coatings (such as SiC) are applied. The test records the mass loss rate (precision balance, accuracy ±0.1 mg), crack density (SEM, magnification 50-200×), SiO_2 film state and resistivity change (four-probe method). Environmental stress is simulated by introducing trace corrosive gases (such as SO_2) to evaluate the impact on life.

The test results show that thermal stress is the main factor affecting the life of $MoSi_2$ components. Rapid temperature rise and fall leads to stress concentration in the transition zone between the hot end and the cold end, increases the density of microcracks, and shortens the life. The W-type component has a more

电话/TEL：0086 592 512 9696

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uniform stress distribution due to the multi-hot end design, and its life is better than that of the U-type. Mechanical stress (such as vibration or improper installation) aggravates crack propagation, reduces fracture toughness, and reduces life. Surface coating significantly alleviates the stress coupling effect, and uniform coating reduces spalling caused by thermal stress and prolongs life. Doping modification (such as Y_2O_3) improves grain boundary strength and reduces stress sensitivity. Environmental stress (such as corrosive atmosphere) accelerates the degradation of SiO_2 film, and the atmosphere needs to be strictly controlled. The test requires calibrated thermocouples (accuracy ±1°C) and clamps. The data guides the optimization of design (such as increasing the bending radius) and operating parameters through stress-life models (such as Weibull analysis) to ensure the long-term reliability of $MoSi_2$ components in high temperature and complex stress environments.

5.9 Cracking, bending and end ablation mechanisms

During long-term high-temperature operation, molybdenum disilicide heating elements often fail due to cracking, bending, and end ablation. These problems will not only reduce their performance stability, but also directly affect the safe operation and service life of the entire heating system.

Most cracking phenomena are related to thermal stress. When the heating element heats up or cools down rapidly in a high temperature environment, the temperature gradient between the inner and outer layers of the material is large, which can easily cause uneven thermal expansion inside the material, thereby causing thermal stress concentration. If the structural design is unreasonable, the geometric dimensions are asymmetric, or there are microscopic defects in the components (such as pores and inclusions), thermal stress will cause microcracks to expand and eventually form macroscopic cracks. In addition, if the thickness of the silicon oxide film formed during the oxidation process is uneven, it may also induce cracking due to stress differences, especially during high-temperature sudden cooling or shutdown cooling.

Bending often occurs when the suspension or support structure is unstable during use, or when the material undergoes plastic deformation at high temperatures due to gravity or external mechanical forces. Although $MoSi_2$ is a brittle ceramic with low plasticity, its structure will undergo a certain degree of viscous flow under high temperature conditions (over 1500°C), especially thin-section and long cantilever structures, which are prone to bending under the action of their own weight at high temperatures. Once the bend is formed, the risk of crack propagation during reheating also increases.

End ablation is a common local failure phenomenon of $MoSi_2$ heating elements, mainly concentrated in the area connected to the electrode or where high current density is concentrated. This area often suffers from severe oxidation or evaporation due to excessive contact resistance, arc breakdown, heat accumulation or insufficient local air circulation. Under high temperature and high current conditions, local hot spots may form on the surface of $MoSi_2$, resulting in increased silicon volatilization and destruction of the protective film structure, thus forming ablation pits or melt cavities. In addition, if the end is not properly processed, such as insufficient removal of the oxide film, poor welding quality or insufficient contact area, the ablation process will also be accelerated.

In order to delay or avoid the above failures, it is necessary to optimize the structural design, installation process, electrical control and use environment, etc. For example, adopting a reasonable support method to reduce thermal stress concentration, controlling the heating rate to reduce the risk of thermal shock, improving the end conductive contact structure to reduce contact resistance, and ensuring the integrity of the oxide film can effectively extend the service life of the component.

5.10 Microstructure Analysis and Failure Mode Study

Microstructure analysis is the core means to understand the failure mechanism of $MoSi_2$ heating elements, which can reveal the essential reasons for the physical, chemical and mechanical changes in high temperature environments from the material body level. By microscopically observing the cross-section, surface and internal structure of the element before and after work, the grain structure, phase boundary changes, oxide film growth behavior and potential microcrack distribution can be identified.

In a high-temperature oxidation environment, a dense SiO_2 protective film will form on the surface of $MoSi_2$ material , and there is a clear interface between the film and the substrate. If high-temperature oscillation or chemical corrosion occurs during long-term use, it may cause interface peeling or form a porous oxide layer, affecting the protective performance. In addition, microscopic analysis often reveals the presence of a small amount of second phase particles in $MoSi_2$, such as Mo_5Si_3 , which also have a certain effect on the overall structural stability at different oxidation degrees.

Failure mode research mainly focuses on crack propagation paths, oxide layer rupture mechanisms, element diffusion trends, and phase change behaviors. Microscopic analysis is often carried out in conjunction with scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS), which can clearly show that cracks mostly originate from weakly bonded areas at grain boundaries, or macroscopic damage is caused by pore connections induced by oxidation stress. In addition, by analyzing the differences in oxide film thickness formed at different operating temperatures and times, the oxidation kinetics can be inferred, thereby establishing a material degradation rate model.

Research shows that most failures are mainly caused by the combined effects of "oxidation + thermal stress + structural defects", that is, the material forms a protective film under high-temperature oxidation, but the stress difference during the thermal cycle induces the film to rupture, causing the new exposed surface to continue to oxidize, resulting in stress concentration and microcrack expansion, and ultimately leading to the destruction of the overall structure of the material. This cyclic and gradual accumulation pattern is a typical thermal corrosion fatigue behavior.

In order to improve the failure resistance, future research can introduce trace additive elements (such as Al, Zr, etc.) into the $MoSi_2$ matrix to improve the stability of the oxide film, or use a dual-phase or gradient structure design to relieve thermal stress. In addition, by controlling the grain size, optimizing the sintering process and increasing the density, the microstructure uniformity can be effectively improved, the defect rate can be reduced, and the overall failure resistance can be improved.

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$MoSi_2$ Heating Element Introduction

1. Overview of $MoSi_2$ Heating Element

Molybdenum disilicide ($MoSi_2$) heating elements are high-performance ceramic electric heating materials widely used in industrial furnace applications. In high-temperature oxidizing atmospheres, $MoSi_2$ forms a dense silica (SiO_2) protective layer on its surface, which effectively prevents further oxidation. It exhibits excellent oxidation resistance and thermal stability, allowing stable operation under high temperatures for extended periods.

2. Features of $MoSi_2$ Heating Element

Low thermal expansion coefficient: Well-matched with common ceramic substrates, minimizing the risk of cracking caused by thermal stress.

Excellent oxidation resistance: Forms a dense SiO_2 protective film on the surface, effectively preventing material degradation from oxidation.

Extremely high working temperature: Capable of continuous operation up to 1700°C, and a maximum usage temperature of 1800°C in oxidizing atmospheres.

Good high-temperature electrical resistance characteristics: $MoSi_2$ exhibits relatively stable resistivity at high temperatures, with only a gradual increase in resistivity at elevated temperatures.

3. Specifications of $MoSi_2$ Heating Element

Model (d1/d2)	Hot End Diameter (d1)	Cold End Diameter (d2)	Hot Zone Length (Le)	Cold Zone Length (Lu)	Common Types
φ3/6	3 mm	6 mm	100–300 mm	150–250 mm	Straight / U-type
φ4/9	4 mm	9 mm	100–500 mm	200–300 mm	Straight / U-type
φ6/12	6 mm	12 mm	100–600 mm	200–350 mm	Straight / U-type / W-type
φ9/18	9 mm	18 mm	150–800 mm	250–400 mm	Straight / U-type / W-type
φ12/24	12 mm	24 mm	200–1000 mm	300–500 mm	Straight / U-type / W-type

4. Typical Applications of $MoSi_2$ Heating Element

High-temperature sintering furnaces in the ceramics and powder metallurgy industries

Heat treatment equipment for steel and non-ferrous metals

High-temperature laboratory furnaces

Diffusion, annealing, and oxidation processes in the semiconductor and photovoltaic industries

5. Purchasing Information

Email: sales@chinatungsten.com; Phone: +86 592 5129595; 592 5129696

Website: www.molybdenum.com.cn

Chapter 6 Installation of $MoSi_2$ Heating Elements

6.1 Pre-installation preparations

installing the $MoSi_2$ heating element, systematic preparation is required to ensure the smooth operation of subsequent operations and avoid damage to the element or performance degradation due to improper operation. First, the specifications, voltage levels, power parameters and dimensions of the heating element should be verified to match the equipment according to the design drawings and instructions for use of the heating equipment. If necessary, a physical comparison should be carried out to prevent the system operation from being affected by model errors.

Secondly, check whether the heating furnace cavity structure, support device, electrode fixture and insulation material are intact, especially to confirm whether the installation location is clean, free of impurities, and has good insulation performance. The furnace must be kept dry to prevent moisture from interfering with the high-temperature oxide film or causing a short circuit.

The tools and auxiliary materials used in the installation process should also be prepared in advance, including ceramic brackets, stainless steel clamps, torque tools, insulating gaskets and high-temperature resistant conductive materials. Operators must wear clean insulating gloves and are strictly prohibited from touching the heating parts of $MoSi_2$ components with bare hands to avoid oil pollution affecting the formation of oxide film.

In addition, basic safety training should be provided to the installers to clarify the operating procedures, precautions, and protective measures that need to be followed during the transportation and handling of components. For new equipment used for the first time, an empty furnace temperature rise test should also be performed to verify whether the electrical control system and the thermal expansion behavior of the furnace body meet expectations.

6.2 Detailed Installation Steps

The installation of $MoSi_2$ heating elements should be carried out strictly in accordance with the standard steps to ensure that they have good electrical contact, thermal support and oxidation protection capabilities in actual operation. The following are the key steps of the standardized installation process:

The first step is to confirm the positioning: confirm the installation position of each heating element according to the equipment drawings and component identification. Pay special attention to the electrode symmetry and balance when multiple elements are connected in parallel to avoid local overheating caused by uneven load. The second step is to fix the support: place the $MoSi_2$ heating element on a ceramic bracket or support structure, and adjust its position appropriately to ensure that the heating part is centered and unobstructed with the furnace space. The support structure should have a certain degree of flexibility to adapt to the deformation of the element during thermal expansion and avoid cracking caused by mechanical constraints. The third step is electrode connection: Use a special electrode fixture to firmly connect the conductive end to the power lead. The fixture must be pressed but not excessively to prevent the component from breaking. The connection surface should be kept clean, and high-temperature conductive paste can be used to improve the contact resistance if necessary. During installation, the electrode and the cable should be isolated by appropriate insulating materials to prevent arc discharge. The fourth step is inspection and fine-tuning: After all components are connected, check their installation height, levelness and parallelism to ensure that each component is evenly stressed and reasonably arranged. In particular, check whether the fixture is symmetrical and uniform to prevent uneven current distribution.

Step 5, system test: Before turning on the power, use a multimeter or insulation tester to check whether the resistance value is within the normal range. After turning on the power, first conduct a preheating test with a low voltage for a short time to observe whether there is abnormal heating, sparks, abnormal noise, etc. After confirming that everything is normal, increase the temperature step by step. Step 6, thermal operation stability: Before formal production, it is recommended to conduct a complete heating-insulation-cooling cycle to verify the stability of the component working state and the uniformity of the heat distribution of the equipment. If any abnormal phenomenon is found, the machine should be stopped immediately for inspection to avoid irreversible damage to the components.

Through standardized installation steps, the failure rate of molybdenum disilicide heating elements in early operation can be effectively reduced, ensuring their long-term stable operation, extending their service life, and laying a good foundation for the safe and efficient operation of high-temperature equipment.

6.3 Installation Notes

During the installation of $MoSi_2$ heating elements, special attention should be paid to a series of key details to avoid damage to the element, abnormal furnace or unstable system operation due to operating errors. First of all, the heating element is a brittle ceramic material and should be handled with care during transportation and installation. It is strictly forbidden to be hit, bent or impacted by gravity. In particular, when tightening the electrode clamp, excessive torque should not be used to prevent local stress concentration from causing cracks in the element.

Secondly, the surface of the component must be kept clean, especially the heating part. It is strictly forbidden to contact with grease, moisture or impurities to avoid affecting its high-temperature oxidation behavior. Operators need to wear clean insulating gloves to ensure that the surface of the component will not be artificially contaminated during the entire installation process.

Furthermore, the connection between the electrode and the wire should ensure good contact and uniform clamping to avoid end ablation or abnormal temperature due to excessive contact resistance. At the same time, the spacing between components should be kept consistent to avoid overload and burning of some components due to uneven thermal field or current deviation. In addition, special attention should be paid to the temperature, humidity and cleanliness of the installation environment. The inside of the furnace should be dust-free and water-free. If it is a humid environment, it needs to be fully dried to avoid breakdown or insulation damage caused by water vapor during high-temperature operation.

6.4 Safety Operation Specifications

To ensure the safe and stable operation of the $MoSi_2$ heating element system, operators must strictly abide by the following safety regulations: Before powering on, you must confirm that all wiring is correct, the insulation is in good condition, and the control system functions normally. Wear insulating gloves, goggles and protective clothing when operating the equipment. It is strictly forbidden to touch high-temperature parts or live structures with bare hands. The component should be heated slowly to avoid thermal shock caused by sudden power-on. Especially when it is used for the first time or restarted after long-term disuse, a step-by-step heating method should be used to allow the component to gradually adapt to the thermal environment. It is strictly forbidden to open the furnace door or touch the surface of the components without authorization during operation. Inspection or observation should be carried out after power off and sufficient cooling. If any abnormality is found (such as sparks, arcs, abnormal noises, local redness, etc.), power off and check immediately. Forced operation is strictly prohibited. When replacing components or electrode fixtures, the main power supply should be cut off first and the residual voltage should be confirmed to be released to ensure that the operating environment is in a completely safe state. Regularly checking whether the electrical wiring is loose, whether the clamps are aging, and whether there is carbon or dust accumulation in the furnace is an important measure to ensure long-term safe operation.

6.5 Common Faults and Maintenance Guide

During use, the following typical faults may occur in the molybdenum disilicide heating element, and maintenance personnel should have basic judgment and processing capabilities:

End burnout : usually manifested as local melting or blackening of the electrode connection. Possible causes include excessive contact resistance, arc discharge or loose cables. Check whether the clamp is pressed tightly, whether the contact surface is clean, and replace the burned parts appropriately.

Surface cracks : Mostly caused by thermal shock or mechanical stress. Maintenance recommendations include adjusting the heating rate, optimizing the support structure and regularly inspecting components for micro cracks.

Uneven heating : may be caused by inconsistent component spacing, uneven power distribution or performance degradation of individual components. The heating zone should be rearranged and the resistance value of each group of components should be tested.

Component breakage : often caused by improper handling, uneven installation force or long-term overload. The operation records should be reviewed to check for external force interference and replace new components.

Startup failure : If the system cannot heat up normally, it may be due to circuit failure, abnormal power control module or component damage. Check the power input, electrode contact and control output one by one.

To extend the service life of components, it is recommended to conduct a routine inspection once a week, including whether the electrode connection is firm, whether the furnace is clean, and whether the temperature rise is normal. For equipment running at a high frequency, comprehensive maintenance should be carried out every quarter, and operating parameters should be recorded for long-term trend analysis.

6.5.1 Causes and solutions for heating element breakage

molybdenum disilicide ($MoSi_2$) heating elements is a common failure mode in high-temperature operation, which directly affects the equipment's operating stability and production efficiency. Fracture is mainly caused by factors such as thermal stress, mechanical stress, material defects and improper operating conditions. As an intermetallic compound, $MoSi_2$ has high hardness but low fracture toughness (about 2-3 $MPa \cdot m^{1/2}$). It is easy to produce microcracks and expand under complex stress, leading to fracture. Analyzing the cause of fracture and taking targeted solutions can significantly improve the life of the component, which is suitable for high-temperature processes such as ceramic sintering and glass melting.

Causes of fracture: Thermal stress concentration: Rapid temperature rise and fall causes excessive temperature gradient in the transition zone between the hot end and the cold end. The difference in thermal expansion coefficient (about $8.1 \times 10^{-6} K^{-1}$) causes high thermal stress and induces cracks. Frequent thermal cycles aggravate the propagation of microcracks. Mechanical stress: Improper installation or vibration during operation causes mechanical stress concentration, especially at the bends of U-shaped or W-shaped components. Material defects: Porosity (density <98%), grain boundary impurities (such as Fe, Al) or uneven grain size during the manufacturing process reduce fracture toughness, and cracks are easy to propagate along defects. Improper operating conditions: Excessive power density leads to local overheating, and staying in the "plague" temperature range of 400-700℃ for too long generates non-protective oxides (such as MoO_3), which weakens the strength of the material.

Solution: Optimize the heating and cooling rate: control the heating and cooling rate at 5-10℃/min, quickly pass 400-700℃, and reduce thermal stress. Use proportional control power supply (voltage 20-100 V) to achieve a smooth temperature curve and reduce stress concentration in the transition zone between the hot end and the cold end. Improve the installation design: Use high-purity alumina brackets to match the characteristics of $MoSi_2$ to reduce mechanical stress. The clamps are moderately tight to avoid over-tightening or vibration. W-type components are preferred for large furnaces because of their more uniform stress distribution due to the multi-hot end design. Improve material quality: Use hot pressing sintering (density ≥98%) and doping modification (such as Y_2O_3 , 0.1-1 wt%) to optimize grain boundary strength, control grain size, and reduce pores and impurities. Surface polishing reduces crack initiation points. Standardize operating conditions: maintain a power density of 15-20 W/cm², control the oxidizing atmosphere, and avoid reducing or high humidity environments that damage the SiO_2 film. Regularly calibrate the thermocouple (accuracy ±1°C) and the power supply system to prevent local overheating. Surface coating: Apply SiC or Al_2O_3 coating to improve thermal shock resistance and strength and reduce crack propagation. CVD coating is more effective due to its high adhesion (critical load of scratch test >3 kg).

Implementation suggestions : Fracture failure analysis needs to be combined with SEM (magnification 50-200×) to observe crack morphology and XRD analysis of phase composition to determine the cause of fracture. Record the number of thermal cycles and power changes during operation to establish a life prediction model. Optimizing design and operating parameters can reduce the risk of fracture by 30-50% and extend the life of $MoSi_2$ components to more than 5,000 hours.

6.5.2 Causes of oxide layer peeling and regeneration treatment

The SiO_2 protective film of $MoSi_2$ heating elements is the key to their anti-oxidation in oxidizing atmospheres. Peeling will lead to substrate exposure, accelerate oxidation degradation, and significantly shorten service life. Oxide layer peeling is mainly caused by thermal stress, coating defects, operating environment and long-term aging. Testing and regenerating the oxide layer peeling problem can effectively restore component performance and is suitable for high-temperature oxidizing environments such as semiconductor manufacturing and ceramic sintering.

Causes of peeling: Thermal stress drive: Rapid temperature rise and fall or frequent thermal cycles cause the difference in thermal expansion coefficients between the SiO_2 film and the $MoSi_2$ substrate to produce high shear stress, causing the film layer to crack or peel off. Coating defects: Uneven surface coating thickness or insufficient adhesion (critical load of scratch test <2 kg) leads to local peeling, destroying the integrity of the SiO_2 film . Manufacturing defects (such as pores or cracks) increase the risk of peeling. Impact of operating environment: High humidity (humidity>70%) or corrosive atmosphere causes hydration or chemical corrosion of the SiO_2 film , reducing adhesion. 400-700℃ "plague" oxidation generates non-protective MoO_3 , destroying the film structure. Long-term aging: At 1800℃, close to the use limit of $MoSi_2$, Si volatilizes and causes the SiO_2 film to become thinner, and the film layer cracks or peels off after long-term operation.

Regeneration treatment method: Clean the surface: After stopping the furnace, use a soft brush or compressed air to remove loose oxides in the peeling area. If necessary, wash it lightly with a dilute acid solution (pH 4-5) and dry it thoroughly to avoid residual corrosive substances. High temperature regeneration: Run at 1500-1600℃ in an oxidizing atmosphere for 2-4 hours to promote the regeneration of SiO_2 film. Pass 400-700℃ quickly to avoid "plague" oxidation. Recoating: Use plasma spraying or CVD technology to recoat SiC or Al_2O_3 in severely peeled areas to ensure uniform thickness. CVD coating is more suitable for high-demand scenarios due to its high density. Optimize operating parameters: Reduce the heating and cooling rate to 5-10°C/min, control the power density to 15-20 W/cm², and avoid local overheating. Use proportional control power supply and precise thermocouples (accuracy ±1℃) to maintain a stable thermal field. Improve environmental control: Maintain an oxidizing atmosphere in the furnace and strictly control humidity and corrosive gas content. Check the furnace seal regularly to prevent moisture or contaminants from entering.

Implementation suggestions : For peeling analysis, the film morphology should be observed by SEM and the chemical composition should be analyzed by EDS to determine the peeling mechanism. After regeneration, the resistivity and mass loss rate should be tested (precision balance, accuracy ±0.1 mg) to verify the recovery effect of SiO_2 film .

6.5.3 Daily maintenance methods for heating elements

$MoSi_2$ heating elements is the key to extending service life, ensuring stable operation and reducing maintenance costs. Maintenance focuses on maintaining the integrity of the SiO_2 film, preventing stress damage and maintaining a clean environment in the furnace, which is suitable for high-temperature applications such as ceramics, glass, and semiconductors. Standardized maintenance methods can reduce the risk of failures such as fracture, oxide layer peeling, and resistivity drift.

Maintenance method: Regularly check the surface condition: After every 500-1000 hours of operation, stop the furnace to check the surface of the $MoSi_2$ element (hot end and cold end), and use an optical microscope to observe the integrity of the SiO_2 film, cracks or signs of peeling. Gently brush to remove loose dust and record abnormal areas to evaluate life. Clean the furnace: Clean the furnace every month or after every 100 thermal cycles, using compressed air or a soft brush to remove oxides, metal impurities (such as Fe_2O_3) or volatile deposits (such as alkali metal compounds) to prevent contamination of the SiO_2 film or corrosion. Control operating conditions: Maintain an oxidizing atmosphere and quickly pass 400-700°C to avoid "plague" oxidation. Monitor power density and cold end temperature to prevent overheating or resistivity drift. Check electrical connections: Check the clamp and power connection every 1000 hours, remove oxide or carbide deposits, and ensure good contact. Calibrate the proportional control power supply and thermocouple (accuracy ±1°C) to avoid voltage fluctuations or temperature control deviations. Maintain the bracket and installation: Check the high-purity alumina bracket to ensure that there are no cracks or deformations, and keep it matched with the thermal expansion of $MoSi_2$. Adjust the tightness of the clamp to prevent mechanical stress concentration, and lubricate the connectors regularly (use high-temperature lubricant). Record operation data: Establish an operation log to record the number of thermal cycles, temperature curves, power density and resistivity changes (measured by four-probe method). Predict the life through data analysis (such as Weibull model) and replace aging components in advance. Surface coating protection: If SiC or Al_2O_3 coating is used, check the coating integrity regularly and apply recoat (CVD or plasma spray) if necessary. Avoid mechanical scratches or chemical corrosion (such as acidic cleaners) to damage the coating.

Implementation suggestions : Develop a maintenance plan and train operators to implement it in a standardized manner. Use SEM and EDS to analyze failed samples and optimize maintenance strategies. Strictly control the atmosphere and cleanliness in the furnace, and optimize the component layout in combination with thermal field simulation to reduce maintenance costs by 20-30% and ensure that $MoSi_2$ components can operate stably for more than 5,000 hours at 1,500°C. Pay attention to safety during maintenance. After stopping the furnace, wait until the temperature drops to room temperature and disconnect the power supply to avoid electric shock or burns.

6.5.4 Heating element replacement and recycling technology

The replacement of heating elements is a key link to ensure the stable operation of the $MoSi_2$ heating system. As the use time increases, the elements will degrade or even break due to factors such as thermal fatigue, oxidation damage or mechanical damage. They must be replaced in time to prevent equipment failure and production interruption. During the replacement process, the operating procedures should be strictly followed to ensure safety and installation quality.

Before replacement, first disconnect the furnace power supply and wait for the components to cool to a safe temperature to avoid burns and secondary damage caused by thermal stress. Avoid strong pulling and collision during disassembly, and gently separate the components and electrode fixtures to prevent damage to the surrounding structure. The disassembled old components should be classified and stored for subsequent recycling and reuse.

Recycling and reuse technology is of great significance in the application of molybdenum disilicide heating elements. Molybdenum disilicide materials themselves are of high value. Recycling not only saves costs, but also conforms to the concept of green environmental protection. Common recycling processes include the collection of old components, mechanical crushing, chemical treatment and material purification. By removing the oxide layer and impurities, high-purity molybdenum and silicon elements are extracted for the re-preparation of new heating elements or other molybdenum-based materials.

In addition, some slightly oxidized and undamaged components can continue to be used after surface cleaning and oxide layer regeneration, extending their lifespan. Advanced recycling technologies also include vacuum reduction, hot isostatic pressing and other processes to maximize the restoration of material properties. Enterprises should establish a complete recycling system, equipped with specialized equipment and technicians to ensure a safe and efficient recycling process.

6.6 Typical installation methods in industrial furnaces

There are various ways to install $MoSi_2$ heating elements in industrial furnaces. They are usually designed according to the furnace structure, process requirements and element specifications, striving to achieve uniform heating, high efficiency and easy maintenance. The following are several typical installation methods:

Suspension installation : This type of installation is common in atmosphere protection furnaces and vacuum furnaces. The heating element is suspended on the top or both sides of the furnace and fixed with the help of insulating brackets to ensure that the element can expand freely and avoid contact with the furnace wall or other elements. This method is convenient for element replacement and maintenance and is suitable for working conditions that require quick element replacement.

Embedded installation : The heating element is directly embedded in the furnace refractory material or ceramic bracket to form a stable support structure. This method is stable and less susceptible to mechanical impact, and is suitable for industrial furnaces that operate continuously at high temperatures. The disadvantage is that replacement is more complicated and requires disassembly of part of the refractory material.

Bracket fixed installation : Use special metal or ceramic brackets to fix the heating elements in different positions in the furnace, such as the bottom, side wall or top. The bracket design must take into account thermal expansion and insulation performance to ensure that the elements are evenly stressed. This method is suitable for larger industrial furnaces and can achieve precise layout and optimize thermal field distribution.

Flat-lay installation : Lay the components flat on the heating area, such as a heating plate or platform, commonly used in flat furnaces and annealing furnaces. Flat-lay installation can provide uniform heat distribution, but requires the components to be well flat and supported to prevent bending and deformation.

Coil installation : The heating elements are arranged in a spiral or coiled form, suitable for cylindrical or vertical kilns. This method can save space, increase the heating area, and facilitate the adjustment of power density.

In practical applications, multiple installation methods are often combined to meet the needs of complex processes. The design must fully consider the thermal expansion characteristics of the components, electrical insulation requirements, ease of installation and removal, and environmental factors such as atmosphere type and temperature gradient. In addition, during the installation process, ensure that the heating element is firmly connected to the power supply and well insulated to avoid leakage and local overheating. Regularly check the installation status and adjust the brackets and clamps in time to ensure that the thermal field in the furnace is uniform and stable, thereby improving the heating efficiency and the service life of the element.

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电话/TEL：0086 592 512 9696
CTIAQCD-MA-E/P 2018-2024V
sales@chinatungsten.com

Chapter 7 Testing Standards and Certification of $MoSi_2$ Heating Elements

7.1 Heating element performance test method

$MoSi_2$ heating elements is an important part of ensuring their quality and reliability, covering the determination of multiple key indicators, including electrical properties, mechanical properties, thermal properties, and durability. First of all, the electrical performance test mainly involves the determination of the resistance value and temperature coefficient of the element. Through precision resistance measuring instruments, the resistance change of the element is tested under different temperature environments to evaluate the stability and consistency of its electrical performance. The uniformity and linear change of resistance are crucial to the design and use of heating elements.

Mechanical property tests mainly include hardness tests and bending tests. Hardness tests usually use Vickers or Rockwell hardness testers to measure the hardness changes of components under heating and cooling conditions, reflecting the mechanical strength and wear resistance of the material. The bending test applies a certain mechanical stress to observe the elastic deformation capacity and breaking point of the component to evaluate its ability to resist mechanical damage.

Thermal performance testing includes the determination of thermal expansion coefficient and thermal stability testing. The thermal expansion coefficient test uses a thermal expansion instrument to measure the change in length of the component during the heating process to ensure that sufficient thermal expansion space is reserved during the design to avoid damage caused by thermal stress. The thermal stability test uses a high-temperature continuous heating experiment to observe the resistance, morphology and structural changes of the component to evaluate its long-term stability in a high-temperature environment.

In addition, oxidation resistance testing is an important indicator for evaluating the service life of $MoSi_2$ heating elements. By conducting long-term heating experiments in a simulated oxidation environment, the formation, thickness and peeling of the oxide film are detected to determine the oxidation resistance of the element. Failure mode analysis combines fracture analysis and microstructure testing to help identify potential weaknesses and failure mechanisms of heating elements.

These test methods complement each other and comprehensively reflect the performance level of molybdenum disilicide heating elements, providing scientific basis and technical guarantee for production and application.

7.2 Analysis of ISO, ASTM and other standards

The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have developed a number of standards for heating elements and related materials, covering aspects such as product quality, test methods, and safety regulations, which play a key role in ensuring the quality and performance of $MoSi_2$ heating elements.

In terms of ISO standards, the main standards related to $MoSi_2$ heating elements include material composition analysis, dimensional tolerance, mechanical properties testing and environmental adaptability testing. For example, the ISO 9001 quality management system standard ensures the systematic and continuous improvement of quality control during the production process. The ISO 22007 series involves thermal expansion test methods for materials, providing a reference for design and use. ISO standards for electronic ceramics and high-temperature resistant materials cover the evaluation of electrical and thermal properties.

ASTM standards have a long history and are widely used in the field of material testing. The ASTM E1131 standard specifies a general procedure for thermal analysis of materials, which is suitable for determining the thermal stability and phase change behavior of $MoSi_2$ components. The ASTM E384 standard covers microhardness test methods and is widely used for hardness evaluation. ASTM E1820 provides guidance for fracture toughness testing to help analyze the fracture behavior of components. There are also standards such as ASTM B193 for resistivity measurement of metallic materials to ensure the accuracy of electrical performance testing. In addition, ISO and ASTM both have corresponding guidelines for safety specifications and performance requirements for heating elements for industrial furnaces, such as the electrical safety standard IEC 60519 series, which covers the design and operation safety of high-temperature electric heating equipment. These standards are of great guiding significance for manufacturers to design $MoSi_2$ heating elements that meet the requirements of the international market.

In actual applications, companies often combine ISO and ASTM standards to develop internal testing processes to ensure that products meet both international standards and customer-specific needs. The calibration of testing equipment and the qualification certification of operators are also usually carried out in accordance with relevant standards to improve the reliability and authority of test results.

7.3 Environmental adaptability test

Environmental adaptability testing is a key link in evaluating whether molybdenum disilicide heating elements can operate stably in various working environments. This type of test mainly simulates the performance of heating elements under different conditions such as temperature, humidity, atmosphere composition and mechanical vibration. First, the high temperature cycle test detects the influence of thermal stress caused by thermal expansion and contraction of the element on the material structure and performance through repeated heating and cooling, and verifies its thermal fatigue resistance. The wet heat environment test simulates the use under high humidity conditions, observes the stability of the oxide layer on the surface of the element and whether the electrical properties are affected, and ensures that the heating element will not fail in insulation or corrode in a humid environment. In addition, the atmosphere adaptability test focuses on simulating the behavior of the heating element in an oxidizing, reducing or inert atmosphere. By controlling the atmosphere composition in the furnace, the oxidation rate and anti-oxidation performance of the heating element in different atmospheres are examined to ensure that it maintains a good service life in complex working conditions. The mechanical vibration and impact test verifies whether the element and its mounting structure can resist mechanical damage caused by vibration during transportation and operation.

Environmental adaptability testing can fully reflect the reliability of heating elements in actual applications, provide a scientific basis for material selection, design and maintenance, and reduce the risk of failure caused by environmental factors.

7.4 Failure Modes and Life Prediction Methods

Failure mode analysis is the basis for understanding the damage mechanism of $MoSi_2$ heating elements and extending their service life. Common failure modes include thermal fatigue cracking, oxide layer peeling, fracture caused by mechanical stress, and local ablation. Through macroscopic observation and microstructural analysis of failed components, the starting position and expansion path of cracks can be revealed, and material changes before failure can be evaluated, such as coarse grains, increased pores, and abnormal oxide layer thickness.

Life prediction usually uses accelerated life tests combined with theoretical models. Accelerated tests quickly replicate the damage process that components may encounter during long-term use by increasing the operating temperature, increasing the number of thermal cycles, or increasing the mechanical load, and collect failure data. Using these data, combined with relevant theories of fracture mechanics, thermodynamics, and materials science, a mathematical model is established to predict the service life of heating elements under normal operating conditions. Commonly used models include the Arrhenius thermal activation model and the Coffin-Manson fatigue model. In addition, statistical analysis based on failure data, such as the Weibull distribution, helps to evaluate the reliability and life distribution characteristics of the product. Through life prediction, manufacturers can optimize component design and material selection, while providing users with reasonable maintenance and replacement cycle recommendations to reduce failure rates and operating costs.

7.5 Safety and electrical code requirements

Safety and electrical specifications are the basis for ensuring the safe and stable operation of $MoSi_2$ heating elements and their systems. The working temperature of the heating element is extremely high and involves high current switching. The relevant electrical safety standards must be strictly followed to prevent accidents such as electric shock, short circuit and fire. Generally, the insulation resistance of the heating element is required to reach the specified value, and its insulation condition is regularly tested during use to prevent leakage caused by insulation aging.

The electrical connection part should use terminals, insulation materials and connection processes that meet national or international standards to ensure good contact and sufficient mechanical strength and heat resistance. The grounding system should be designed reasonably to effectively reduce the risk of electric shock. The power supply system should be equipped with overload protection, leakage protection and short-circuit protection devices to cut off the power supply in time under abnormal circumstances to ensure the safety of personnel and equipment. In addition, installation and maintenance personnel must comply with safety operating procedures and be equipped with necessary protective equipment. Warning signs and isolation facilities should be set up in high-temperature working areas to prevent accidental touch and burns. Safety certifications of related equipment and components, such as CE certification and UL certification, also provide support for market access and safety assurance.

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Chapter 8 Application of $MoSi_2$ Heating Elements

8.1 Application of $MoSi_2$ Heating Elements in Metallurgical Industry

Molybdenum disilicide ($MoSi_2$) heating elements are widely used in metal smelting, heat treatment and high-temperature sintering processes in the metallurgical industry due to their excellent high-temperature performance, good oxidation resistance and stable electrothermal characteristics. The thermal conductivity, thermal expansion coefficient and positive temperature coefficient resistivity of $MoSi_2$ enable it to provide efficient and uniform heating, meeting the metallurgical industry's needs for high temperature, precise temperature control and long life. $MoSi_2$ elements achieve excellent oxidation resistance through the SiO_2 protective film formed on the surface in an oxidizing atmosphere , which is suitable for long-term operation of metallurgical furnaces. Common $MoSi_2$ element structures (such as U-type, W-type, Φ6/12 or Φ9/18) can be customized according to furnace type and process requirements, and are widely used in metal smelting furnaces, heat treatment furnaces and sintering furnaces. The application optimization of $MoSi_2$ components needs to avoid the "plague" temperature range of 400-700°C, quickly increase and decrease the temperature to reduce the generation of non-protective oxides (a mixture of MoO_3 and SiO_2) , and combine surface coatings (such as SiC or Al_2O_3) to improve thermal shock resistance and life.

In the metallurgical industry, the advantages of $MoSi_2$ heating elements include high power density, stable temperature control and long service life. Its design flexibility supports a variety of furnace types, such as box furnaces, tunnel furnaces and vacuum furnaces, to meet the processing needs of different metal materials. High-purity alumina brackets are required for installation to match the thermal expansion characteristics of $MoSi_2$ and reduce mechanical stress. Electrical connections require the use of low-resistance clamps and proportional control power supplies to ensure operational stability. The application of $MoSi_2$ elements also requires consideration of atmosphere control to avoid reduction or high humidity environments that cause SiO_2 film failure.

8.1.1 Metal smelting and heat treatment

$MoSi_2$ heating elements in metal smelting and heat treatment is mainly concentrated in high-temperature smelting furnaces, annealing furnaces and quenching furnaces, and is used to process metal materials such as aluminum, copper, steel, and titanium alloys. Metal smelting requires the furnace temperature to be precisely controlled at 1000-1600°C. The positive temperature coefficient resistivity of $MoSi_2$ elements enables it to adaptively adjust the power and provide a stable high-temperature environment. U-type and W-type $MoSi_2$ elements are commonly used in small and medium-sized smelting furnaces, with a hot end length of 100-500 mm and a power density of 15-20 W/cm^2. They can quickly reach the melting point (such as 660°C for aluminum and 1085°C for copper) and maintain a uniform temperature field. In heat treatment processes such as annealing and quenching, $MoSi_2$ elements provide stable heating at 1200-1500°C, ensuring metal grain refinement and performance optimization. For example, the annealing of steel requires holding at 1200-1300°C, and the thermal conductivity and thermal shock resistance of $MoSi_2$ components support rapid heating and thermal cycling.

$MoSi_2$ elements in metal smelting and heat treatment include high oxidation resistance and long life. In an oxidizing atmosphere, the SiO_2 protective film effectively prevents material degradation, and the mass loss rate at 1500°C is less than 0.2 mg/cm²/1000h. Surface coating can further improve thermal shock resistance and corrosion resistance, and is suitable for metallurgical atmospheres containing trace sulfur or carbon. When installed, U-type elements are suspended vertically, W-type elements are suitable for uniform heating of large furnaces, and the cold end is enhanced by an aluminized coating. During operation, it is necessary to avoid rapid passage through 400-700°C to prevent "plague" oxidation, and the heating and cooling rate is controlled at 5-10°C/min. Maintenance includes regular inspection of the integrity of the SiO_2 film and the connection status of the cold end, and cleaning of furnace impurities (such as iron oxide) to avoid contamination. The limitation of $MoSi_2$ elements is that the operating temperature needs to be lowered in a reducing or vacuum environment to prevent the failure of the SiO_2 film. In practical applications, the optimization of component layout combined with thermal field simulation can significantly improve the efficiency and quality of metal smelting and heat treatment.

8.1.2 High temperature sintering process

$MoSi_2$ heating elements in high-temperature sintering processes mainly involves the sintering of metal powder metallurgy, ceramic composites and special alloys, and is commonly used in the production of high-performance steels, titanium-based alloys and cemented carbides. The sintering process requires precise temperature control at 1300-1800 °C to promote material densification and grain growth. The high power density and stable temperature control of $MoSi_2$ elements make them an ideal choice. W-type and straight rod $MoSi_2$ elements are often used in large sintering furnaces to provide a uniform heat field and are suitable for large-sized workpieces. Spiral elements (hot end diameter 4-9 mm) are suitable for small tube furnaces to meet high-precision sintering needs. The thermal conductivity and positive temperature coefficient resistivity of $MoSi_2$ ensure uniform heat distribution during sintering and reduce workpiece deformation and cracks.

In high-temperature sintering, the oxidation resistance of $MoSi_2$ elements is a key advantage. The SiO_2 protective film remains stable at 1500-1800°C (thickness 10-15 μm), with a mass loss rate of <0.5 mg/cm²/1000h, supporting long-term operation. Doping modification (such as Y_2O_3, 0.1-1 wt%) enhances grain boundary strength, and surface coating (such as Al_2O_3, thickness 10-50 μm) improves thermal shock resistance and corrosion resistance, which is suitable for sintering atmospheres containing trace volatile impurities. When installed, W-type elements are supported horizontally or suspended vertically, and high-purity alumina brackets reduce thermal stress. Copper clamps are used for electrical connections, and proportional control power supplies are used to ensure stability. During operation, the temperature must be quickly passed through 400-700°C to avoid the formation of non-protective oxides, and the heating and cooling rate must be 5-10°C/min to reduce thermal stress ($MoSi_2$ fracture toughness is about 2-3 MPa·m$^{1/2}$).

$MoSi_2$ components in high-temperature sintering include atmosphere sensitivity and maintenance requirements. Sintering atmospheres containing sulfur or carbon may corrode the SiO_2 film , and the oxygen partial pressure and humidity must be strictly controlled. Regular inspection of the component surface (SEM observation of the film layer) and the cold end temperature, and cleaning of furnace impurities (such as metal oxides) can extend the service life. Thermal field optimization (such as finite element simulation) ensures temperature uniformity and reduces defects in sintered workpieces. The high performance of $MoSi_2$ components makes them widely used in the production of aerospace components, cutting tools and wear-resistant materials in high-temperature sintering processes to improve product quality and production efficiency.

8.1.3 Heat treatment equipment

$MoSi_2$ heating elements are widely used in heat treatment equipment in the metallurgical industry, covering annealing furnaces, quenching furnaces, normalizing furnaces and tempering furnaces, to improve the mechanical properties, corrosion resistance and processing properties of metal materials. Heat treatment equipment requires precise control of temperature and uniform thermal field to ensure optimization of metal grain structure and stress relief. The positive temperature coefficient resistivity of $MoSi_2$ elements enables them to provide stable heating in the range of 1200-1500°C, suitable for processing materials such as steel, aluminum alloys, copper alloys and titanium alloys. U-shaped $MoSi_2$ elements are suitable for small heat treatment furnaces with a hot end length of 100-500 mm, providing centralized heating and suitable for small batch production. W-shaped and straight rod-shaped elements are suitable for large continuous heat treatment furnaces with a hot end length of 200-1000 mm, which can cover a large heating area and ensure temperature uniformity.

$MoSi_2$ elements in heat treatment equipment lies in their high oxidation resistance and ability to support frequent thermal cycles. In an oxidizing atmosphere, the SiO_2 protective film ensures long-term stability of the element, which is suitable for long-term heat preservation and rapid temperature rise and fall in the heat treatment process. Surface coatings (such as SiC or Al_2O_3) enhance thermal shock resistance and corrosion resistance, and are suitable for complex metallurgical atmospheres. During installation, the element is fixed by a high-purity alumina bracket, and vertical suspension or horizontal support reduces mechanical stress. The electrical connection uses a low-resistance clamp, and the proportional control power supply ensures precise temperature control. During operation, it is necessary to quickly pass 400-700°C to avoid "plague" oxidation, and the temperature rise and fall rate is controlled at 5-10°C/min. Maintenance includes regular inspection of the SiO_2 film, cold end connection and furnace cleaning to prevent impurity contamination. The limitation of $MoSi_2$ elements is that the use temperature needs to be lowered in a reducing atmosphere, and the atmosphere in the furnace needs to be strictly controlled. Thermal field optimization and regular maintenance ensure the high efficiency and product quality of heat treatment equipment, which is widely used in the automotive, aerospace and machinery manufacturing fields.

8.2 Application of $MoSi_2$ Heating Elements in Ceramic Industry

$MoSi_2$ heating elements are widely used in ceramic firing, glazing treatment and special ceramic material preparation in the ceramic industry. Their high operating temperature, oxidation resistance and electrothermal stability meet the needs of ceramic processes for high temperature and precise temperature control. $MoSi_2$ elements maintain stability in an oxidizing atmosphere through a surface SiO_2 protective film, and are suitable for ceramic firing furnaces, glaze firing furnaces and special ceramic sintering furnaces. U-shaped, W-shaped and spiral $MoSi_2$ elements are customized according to the furnace type. The U-shaped is suitable for small box furnaces, the W-shaped is suitable for large tunnel furnaces, and the spiral type is suitable for high-precision sintering in tube furnaces. High-purity alumina brackets are used for installation, low-resistance clamps are used for electrical connections, and precise temperature control is achieved with a proportional control power supply. The operation needs to pass through 400-700°C quickly to avoid "plague" oxidation, the heating and cooling rate is 5-10°C/min, and the surface coating improves thermal shock resistance and life. The application of $MoSi_2$ elements in the ceramic industry significantly improves the firing quality and production efficiency, meeting the needs of traditional ceramics and advanced ceramics.

8.2.1 Ceramic firing and glazing

$MoSi_2$ heating elements are used in box furnaces, shuttle furnaces and tunnel furnaces in ceramic firing and glazing treatment, and are used to produce daily-use ceramics, architectural ceramics and artistic ceramics. Ceramic firing requires green body sintering and glaze melting at 1000-1400°C. The positive temperature coefficient resistivity of $MoSi_2$ elements provides a stable high-temperature environment to ensure the densification of ceramic green bodies and the gloss of glazes. U-shaped $MoSi_2$ elements are suitable for small furnaces, and W-shaped elements are suitable for large continuous firing furnaces, providing a uniform heat field to reduce ceramic cracking and deformation. Glazing treatment requires precise temperature control to control glaze melting and crystallization. The thermal conductivity of $MoSi_2$ elements supports rapid heating and insulation. The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance, which is suitable for firing atmospheres containing volatile glazes. Installation and operation require control of the atmosphere and heating and cooling rates, and maintenance includes regular inspection of the component surface and furnace cleaning. $MoSi_2$ components improve the efficiency and product quality of ceramic firing and glazing processes and are widely used in ceramic production.

8.2.2 Preparation of special ceramic materials

$MoSi_2$ heating elements are used in sintering furnaces and hot pressing furnaces in the preparation of special ceramic materials. They are used to produce advanced ceramics such as alumina, zirconia, silicon nitride and silicon carbide, and are widely used in aerospace, electronics and medical fields. Special ceramic sintering needs to be carried out at 1400-1800°C to achieve high density and excellent performance. The high power density and precise temperature control capability of $MoSi_2$ elements meet these requirements. W-type and spiral $MoSi_2$ elements are suitable for large and small sintering furnaces, providing a uniform thermal field and reducing material defects. SiO_2 protective film and surface coating ensure the stability of the elements in high-temperature oxidizing atmospheres, and doping modification enhances thermal shock resistance and is suitable for frequent thermal cycles. High-purity alumina brackets are used for installation, electrical connections ensure low-resistance contact, and the atmosphere and heating and cooling rates are controlled to avoid "plague" oxidation. Maintenance includes regular inspection of the components and furnace status to ensure long-term reliability.

8.3 Application of $MoSi_2$ Heating Elements in Photovoltaic Industry

Molybdenum disilicide ($MoSi_2$) heating elements are widely used in the photovoltaic industry for silicon wafer manufacturing and solar cell production equipment due to their high temperature performance, oxidation resistance and electrothermal stability. $MoSi_2$ elements can provide precise temperature control and uniform thermal field, meeting the high temperature and clean environment requirements of photovoltaic processes. It achieves oxidation resistance through the SiO_2 protective film formed on the surface in an oxidizing atmosphere , which is suitable for long-term operation. U-shaped, W-shaped and straight rod $MoSi_2$ elements are customized according to the furnace type. The U-shaped is suitable for small furnaces, and the W-shaped and straight rod types are suitable for large continuous equipment. High-purity alumina brackets are used for installation to match thermal expansion characteristics, low-resistance clamps are used for electrical connections, and proportional control power supplies are used to ensure stability. Operation needs to quickly pass through the "plague" temperature range to avoid the formation of non-protective oxides, and surface coatings (such as SiC or Al_2O_3) improve thermal shock resistance and life.

8.3.1 High-temperature process for silicon wafer manufacturing

$MoSi_2$ heating elements are used in the high-temperature process of silicon wafer manufacturing for single crystal silicon pulling, multicrystalline silicon ingot casting and silicon wafer annealing. These processes require a high temperature environment to melt silicon raw materials, control crystal growth or eliminate crystal defects. The positive temperature coefficient resistivity of $MoSi_2$ elements provides stable heating capabilities. Straight rod and W-type $MoSi_2$ elements are suitable for large single crystal furnaces and ingot furnaces, covering a wide heating area to ensure thermal field uniformity. U-type elements are suitable for small annealing furnaces to meet local high temperature requirements. The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance, which is suitable for the clean environment of silicon wafer manufacturing. During installation, the element is fixed by a high-purity alumina bracket, and the electrical connection ensures low-resistance contact. Operation requires control of the atmosphere and heating and cooling rates to avoid oxidation damage, and maintenance includes regular inspection of the element surface and furnace cleanliness. $MoSi_2$ elements improve the crystal quality and production efficiency of silicon wafer manufacturing and are widely used in the upstream of the photovoltaic industry chain.

8.3.2 Solar cell production equipment

$MoSi_2$ heating elements are used in diffusion furnaces, sintering furnaces and annealing furnaces in solar cell production equipment to manufacture crystalline silicon and thin-film solar cells. The diffusion process requires high temperature to dope phosphorus or boron to form a PN junction, the sintering process combines metal electrodes with silicon wafers, and the annealing process optimizes cell performance. $MoSi_2$ elements provide precise temperature control and uniform thermal fields to meet the requirements of these processes. U-shaped and spiral $MoSi_2$ elements are suitable for small diffusion furnaces and annealing furnaces, and W-shaped elements are suitable for large sintering furnaces to ensure the stability of large-area heating. The SiO_2 protective film and surface coating support the long-term operation of the element in an oxidizing atmosphere, and the thermal shock resistance adapts to frequent thermal cycles. The installation uses a high-purity alumina bracket, and the electrical connection uses a proportional control power supply to achieve precise temperature control. The operation needs to quickly pass through the "plague" temperature range, and maintenance includes checking the SiO_2 film and cleaning the furnace to avoid contamination. $MoSi_2$ elements improve the efficiency of solar cell production and cell performance, and are widely used in the field of photovoltaic power generation.

8.4 Application of $MoSi_2$ Heating Elements in Semiconductor Industry

Molybdenum disilicide ($MoSi_2$) heating elements are widely used in high-temperature processes such as wafer annealing, diffusion processes and epitaxial growth in the semiconductor industry due to their high-temperature performance, oxidation resistance and electrothermal stability. $MoSi_2$ elements can provide precise temperature control and uniform thermal field, meeting the needs of semiconductor manufacturing for clean environment and high-precision temperature control. It has excellent oxidation resistance through the SiO_2 protective film formed on the surface in an oxidizing atmosphere, which is suitable for long-term operation. U-shaped, W-shaped and spiral $MoSi_2$ elements are customized according to the furnace type. U-shaped and spiral types are suitable for small high-precision furnaces, and W-shaped is suitable for large continuous equipment. High-purity alumina brackets are used for installation to match the thermal expansion characteristics of $MoSi_2$ and reduce mechanical stress. Low-resistance clamps are used for electrical connections, and proportional control power supplies are used to ensure stability. Operation needs to pass through the "plague" temperature range quickly to avoid the formation of non-protective oxides, and surface coatings (such as SiC or Al_2O_3) further improve thermal shock resistance and service life. Regularly check the integrity of the SiO_2 film and the status of the cold end connection, clean the furnace to avoid contamination by impurities, and ensure the reliability and efficiency of components in the semiconductor industry.

8.4.1 Wafer Annealing and Diffusion Process

$MoSi_2$ heating elements are used in rapid thermal annealing (RTA) furnaces, diffusion furnaces and oxidation furnaces in wafer annealing and diffusion processes to process silicon wafers and other semiconductor materials. Wafer annealing requires high temperatures to repair lattice defects, activate dopants or improve material properties. The diffusion process forms a PN junction through high-temperature doping (such as phosphorus and boron). The positive temperature coefficient resistivity of $MoSi_2$ elements provides stable heating capabilities and ensures precise temperature control. U-shaped and spiral $MoSi_2$ elements are suitable for small annealing and diffusion furnaces, suitable for high-precision small batch production, and W-shaped elements are suitable for large diffusion furnaces to provide a uniform heat field to process multiple wafers. The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance, which is suitable for a clean semiconductor process environment. During installation, the element is fixed by a high-purity alumina bracket, and the electrical connection ensures low-resistance contact. The operation requires controlled atmosphere and heating and cooling rates to avoid oxidation damage. Maintenance includes regular inspection of the surface of the element and the cleanliness of the furnace to prevent impurities (such as metal ions) from contaminating the wafer. $MoSi_2$ components improve the efficiency and quality of wafer annealing and diffusion processes and are widely used in integrated circuit and power device manufacturing.

8.4.2 Semiconductor Epitaxial Growth

$MoSi_2$ heating elements are used in chemical vapor deposition (CVD) furnaces and molecular beam epitaxy (MBE) equipment in semiconductor epitaxial growth to grow high-quality single crystal films such as silicon, germanium and compound semiconductors (such as GaAs, SiC). Epitaxial growth requires precise control of the thermal field at high temperatures to ensure the crystal quality and uniformity of the film. The high power density and stable temperature control capability of $MoSi_2$ elements meet these requirements. Spiral $MoSi_2$ elements are suitable for small CVD furnaces, providing centralized heating to support high-precision growth. W-type and straight rod elements are suitable for large epitaxial furnaces to ensure thermal field uniformity for large-area wafers. SiO_2 protective film and surface coating support elements for long-term operation in oxidizing atmospheres or trace oxygen environments, and thermal shock resistance adapts to frequent thermal cycles. High-purity alumina brackets are used for installation, and proportional control power supplies are used for electrical connections to achieve precise temperature control. Operation requires rapid passage through the "plague" temperature range, and maintenance includes checking the SiO_2 film and cleaning the furnace to avoid contamination. $MoSi_2$ components improve the quality and production efficiency of epitaxially grown films and are widely used in semiconductor device manufacturing.

8.4.3 High temperature etching equipment

$MoSi_2$ heating elements are used in plasma etching furnaces and thermal etching furnaces in high-temperature etching equipment for patterning of semiconductor wafers. High-temperature etching processes require precise temperature control to optimize etching rate and selectivity and ensure the accuracy of micro-nanoscale structures. The positive temperature coefficient resistivity and uniform thermal field of $MoSi_2$ elements meet these requirements. U-shaped and spiral $MoSi_2$ elements are suitable for small etching furnaces, providing centralized heating to support high-precision processes, and W-shaped elements are suitable for large equipment to ensure temperature consistency of multiple wafers. SiO_2 protective films remain stable in oxidizing atmospheres, and surface coatings (such as SiC or Al_2O_3) enhance thermal shock resistance and corrosion resistance to adapt to corrosive gases (such as chlorine or fluoride) that may be present during etching. During installation, the elements are fixed by high-purity alumina brackets, and low-resistance clamps are used for electrical connections to ensure stability. Operation requires control of atmosphere and heating and cooling rates to avoid oxidation damage. Maintenance includes regular inspection of the surface of the elements and the cleanliness of the furnace to prevent impurities from contaminating the wafers. $MoSi_2$ components improve the processing accuracy and efficiency of high-temperature etching equipment and are widely used in microstructure processing in semiconductor manufacturing.

8.4.4 Vacuum coating equipment

$MoSi_2$ heating elements are used in vacuum coating equipment in physical vapor deposition (PVD) and chemical vapor deposition (CVD) systems to deposit metal, oxide or nitride films, such as TiN, Al_2O_3 , for electrodes or insulating layers of semiconductor devices. Vacuum coating requires high temperatures to evaporate or decompose precursor materials.

The high power density and precise temperature control capabilities of $MoSi_2$ elements ensure the uniformity and quality of the film. U-shaped and spiral $MoSi_2$ elements are suitable for small vacuum coating furnaces to provide local high temperatures to support high-precision deposition. W-shaped and straight rod elements are suitable for large equipment to ensure the uniformity of the thermal field of large-area substrates. In an oxidizing atmosphere or trace oxygen environment, the SiO_2 protective film and surface coating support the long-term operation of the element, and the thermal shock resistance adapts to rapid temperature rise and fall.

The installation adopts a high-purity alumina bracket, and the electrical connection uses a proportional control power supply to achieve stable temperature control. The operation needs to quickly pass through the "plague" temperature range to avoid oxidation damage. Maintenance includes checking the SiO_2 film and cleaning the furnace to prevent contamination. $MoSi_2$ components improve the film quality and production efficiency of vacuum coating equipment and are widely used in the film preparation of semiconductor devices.

8.5 Application of $MoSi_2$ Heating Elements in Glass Manufacturing Industry

Molybdenum disilicide ($MoSi_2$) heating elements are widely used in glass melting and glass processing in the glass manufacturing industry due to their excellent high temperature performance, oxidation resistance and electrothermal stability. $MoSi_2$ elements can provide precise temperature control and uniform heat field, meeting the requirements of glass manufacturing for high temperature, long-term operation and clean environment. Its excellent oxidation resistance is achieved through the SiO_2 protective film formed on the surface in an oxidizing atmosphere , which is suitable for the harsh working conditions of glass furnaces. W-type, U-type and straight rod $MoSi_2$ elements are customized according to the furnace type. The W-type is suitable for large melting furnaces to provide uniform heating, and the U-type and straight rod types are suitable for small and medium-sized processing furnaces. High-purity alumina brackets are used for installation to match the thermal expansion characteristics of $MoSi_2$ and reduce mechanical stress. Low-resistance clamps are used for electrical connections, and proportional control power supplies are used to ensure stability. Operation needs to pass through the "plague" temperature range quickly to avoid the formation of non-protective oxides, and surface coatings (such as SiC or Al_2O_3) further improve thermal shock resistance and service life. Regularly check the integrity of the SiO_2 film and the status of the cold end connection, clean the furnace to avoid contamination by impurities, and ensure the reliability and efficiency of the components in glass manufacturing.

8.5.1 Glass melting

$MoSi_2$ heating elements are used in large melting furnaces and small experimental furnaces in the glass melting process for the production of flat glass, optical glass and specialty glass. Glass melting requires high temperatures to melt raw materials (such as silica sand, soda ash) into uniform liquid glass. The positive temperature coefficient resistivity of $MoSi_2$ elements provides a stable high temperature environment to ensure melting quality and consistency.

W-type $MoSi_2$ elements are suitable for large continuous melting furnaces, covering a wide heating area and providing a uniform heat field to reduce bubbles and streaks in the glass. U-type elements are suitable for small melting furnaces and are suitable for small batch production of specialty glass. The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance to adapt to volatile components (such as borates) that may be present in the glass melt. During installation, the element is fixed by a high-purity alumina bracket, and the electrical connection ensures low-resistance contact. The operation requires controlled atmosphere and heating and cooling rates to avoid oxidation damage.

Maintenance includes regular inspection of the element surface and furnace cleanliness to prevent impurities (such as alkali metal oxides) from contaminating the glass melt. $MoSi_2$ components improve the efficiency of glass melting and product quality and are widely used in architectural, automotive and optical glass manufacturing.

8.5.2 Glass processing

$MoSi_2$ heating elements are used in annealing furnaces, forming furnaces and hot bending furnaces in glass processing technology for forming, annealing and surface treatment of glass products. Glass processing requires precise temperature control to eliminate internal stress, shape or enhance glass performance. The high power density and stable temperature control ability of $MoSi_2$ elements meet these requirements. U-shaped and straight rod $MoSi_2$ elements are suitable for small and medium-sized annealing and hot bending furnaces, providing centralized heating to support the processing of complex-shaped glass. W-shaped elements are suitable for large forming furnaces to ensure temperature uniformity of large-area glass plates.

SiO_2 protective film and surface coating support long-term operation of the elements in an oxidizing atmosphere, and thermal shock resistance adapts to frequent thermal cycles. High-purity alumina brackets are used for installation, and proportional control power is used for electrical connections to achieve precise temperature control. Operation needs to quickly pass through the "plague" temperature range, and maintenance includes checking the SiO_2 film and cleaning the furnace to avoid contamination.

$MoSi_2$ elements improve the accuracy and efficiency of glass processing and are widely used in the production of glass containers, display glass and architectural glass.

8.6 Application of $MoSi_2$ Heating Elements in the Preparation of New Energy Materials

Molybdenum disilicide ($MoSi_2$) heating elements play an important role in the preparation of new energy materials due to their excellent high-temperature performance, oxidation resistance and electrothermal stability. They are widely used in high-demand scenarios such as lithium battery material sintering, hydrogen energy and fuel cell related processes. $MoSi_2$ elements can achieve excellent oxidation resistance through the SiO_2 protective film formed on the surface in an oxidizing atmosphere , which is suitable for long-term high-temperature operation. At the same time, their positive temperature coefficient resistivity characteristics ensure precise temperature control and uniform thermal field distribution. These characteristics enable it to meet the requirements of clean environment, high-precision temperature control and thermal cycle resistance in the preparation of new energy materials. $MoSi_2$ elements have various structures, such as U-type, W-type, spiral type and straight rod type, which can be customized according to different equipment requirements. U-type and spiral type are suitable for small high-precision sintering furnaces, and W-type and straight rod type are suitable for large continuous production equipment. High-purity alumina brackets are used during installation to match the thermal expansion characteristics of $MoSi_2$ and reduce mechanical stress and thermal stress concentration. Low-resistance clamps are used for electrical connections, and stable operation is achieved with proportional control power supply. During operation, it is necessary to quickly pass through the "disease" temperature range to avoid the formation of non-protective oxides. Surface coatings (such as SiC or Al_2O_3) further enhance thermal shock resistance and corrosion resistance, and extend component life. Regular maintenance includes checking the integrity of the SiO_2 film , the cold end connection status, and the cleanliness of the furnace to ensure that there is no impurity contamination and meet the strict requirements for the preparation of new energy materials. $MoSi_2$ elements provide reliable support for the performance improvement and production efficiency of new energy materials by optimizing thermal field design and operating parameters.

8.6.1 Sintering of Lithium Battery Materials

$MoSi_2$ heating elements are widely used in the preparation of positive electrode, negative electrode and solid electrolyte materials in the sintering process of lithium battery materials, and are used to produce key materials such as lithium cobalt oxide, nickel cobalt manganese ternary materials, lithium iron phosphate, graphite negative electrode and solid oxide electrolyte. The sintering of lithium battery materials needs to be carried out at high temperatures to promote crystal growth, improve material density and electrochemical properties. The high power density and precise temperature control capabilities of $MoSi_2$ elements can meet these demanding requirements. U-shaped and spiral $MoSi_2$ elements are suitable for small laboratory sintering furnaces, suitable for the development of new battery materials or small batch production, providing centralized heating to ensure high precision of the process. W-shaped and straight rod elements are suitable for large industrial sintering furnaces, which can cover a wide heating area and provide a uniform heat field to support large-scale production. The SiO_2

protective film remains stable in an oxidizing atmosphere, ensuring the oxidation resistance of the components during the sintering process. The surface coating (such as SiC or Al_2O_3) enhances the thermal shock resistance and corrosion resistance, and adapts to the volatile gases or trace corrosive atmospheres (such as volatiles containing lithium compounds) that may exist during the sintering process. During installation, the components are fixed by high-purity alumina brackets, vertically suspended or horizontally supported to reduce mechanical stress. The electrical connection uses a low-resistance clamp, and a proportional control power supply is used to achieve precise temperature control. The operation requires strict control of the atmosphere in the furnace to avoid the failure of the SiO_2 film due to a reducing or high-humidity environment , and quickly pass through the "plague" temperature range to prevent the formation of non-protective oxides. Maintenance includes regular inspection of the surface condition of the components, cold end connections, and furnace cleanliness, and removal of impurities that may affect the purity of the materials (such as alkali metal oxides). $MoSi_2$ components optimize thermal field design and operating parameters to ensure that lithium battery materials obtain excellent crystal structure and electrochemical properties during the sintering process, significantly improving the capacity, cycle life and safety of the battery. They are widely used in electric vehicles, energy storage systems and consumer electronics.

8.6.2 Hydrogen Energy and Fuel Cells

$MoSi_2$ heating elements are mainly used in the sintering of solid oxide fuel cell (SOFC) materials, the preparation process of hydrogen production reactors and high-temperature components of electrolyzers, and are used to produce electrolytes, anodes, cathode materials, and high-temperature catalyst carriers. The preparation of hydrogen energy and fuel cell materials requires sintering or heat treatment at high temperatures to optimize the microstructure and performance of the materials . The stable high-temperature performance and uniform thermal field distribution of $MoSi_2$ elements can meet these process requirements. Spiral and U-shaped $MoSi_2$ elements are suitable for small experimental furnaces, suitable for the development of new fuel cell materials or catalysts, and provide local high temperatures to support high-precision sintering or heat treatment processes. W-type and straight rod elements are suitable for large industrial furnaces for large-scale production of SOFC components or hydrogen production equipment components to ensure thermal field uniformity to reduce material defects.

The SiO_2 protective film provides reliable anti-oxidation protection in an oxidizing atmosphere, and the surface coating (such as Al_2O_3 or SiC) enhances thermal shock resistance and corrosion resistance, and adapts to the complex atmosphere (such as water vapor or trace reducing gases) that may be involved in the sintering of fuel cell materials. In the preparation of hydrogen production reactors or electrolyzer components, $MoSi_2$ elements support the sintering or heat treatment of high-temperature catalyst carriers to ensure high activity and stability of the catalyst. During installation, the elements are fixed by high-purity alumina brackets, and low-resistance clamps are used for electrical connections. The proportional control power supply is used to achieve precise temperature control to meet the requirements of SOFC materials for strict temperature curves. The operation requires the control of the furnace atmosphere to avoid the high reducing environment from damaging the SiO_2 membrane , and quickly pass through the "plague" temperature range to prevent oxidation damage. Maintenance includes regular inspection of the

SiO_2 membrane , cold end connection and furnace cleanliness to ensure that there is no impurity contamination that affects material performance. $MoSi_2$ components improve the electrochemical performance of fuel cell materials and the efficiency of hydrogen production equipment by optimizing thermal fields and process parameters. They are widely used in clean energy power generation, industrial hydrogen production and energy conversion, providing important support for the commercial development of hydrogen energy technology.

8.7 Application of $MoSi_2$ Heating Elements in Environmental Protection and Catalysis

Molybdenum disilicide ($MoSi_2$) heating elements are widely used in waste gas treatment, catalyst regeneration and solid waste resource recovery in the field of environmental protection and catalysis due to their excellent high temperature performance, oxidation resistance and electrothermal stability. $MoSi_2$ elements can achieve excellent oxidation resistance through the SiO_2 protective film formed on the surface in an oxidizing atmosphere , and are suitable for long-term high-temperature operation. Its positive temperature coefficient resistivity characteristics ensure precise temperature control and uniform thermal field distribution, meeting the requirements of environmental protection and catalytic processes for high temperature, clean environment and corrosion resistance. U-shaped, W-shaped, spiral and straight rod $MoSi_2$ elements are customized according to equipment requirements. U-shaped and spiral types are suitable for small high-precision reactors, and W-shaped and straight rod types are suitable for large continuous processing equipment. High-purity alumina brackets are used for installation to match the thermal expansion characteristics of $MoSi_2$ and reduce mechanical and thermal stresses. Low-resistance clamps are used for electrical connections, and stable operation is achieved with proportional control power supplies. The operation needs to quickly pass through the "disease" temperature range to avoid the formation of non-protective oxides. The surface coating (such as SiC or Al_2O_3) further enhances the thermal shock resistance and corrosion resistance and prolongs the life of the components. Regular maintenance includes checking the integrity of the SiO_2 film , the cold end connection status and the cleanliness of the furnace to ensure that there is no impurity contamination and meet the high standards in the field of environmental protection and catalysis. $MoSi_2$ elements provide key support for the efficiency and reliability of exhaust gas treatment, catalyst regeneration and solid waste resource utilization by optimizing thermal field design and operating parameters.

8.7.1 Waste gas treatment

$MoSi_2$ heating elements are used in high-temperature incinerators, catalytic oxidation furnaces and pyrolysis furnaces in the waste gas treatment process to treat industrial waste gas, volatile organic compounds (VOCs) and harmful gases (such as NOx, SOx). Waste gas treatment requires high temperature to decompose harmful components or promote catalytic reactions. The high power density and precise temperature control capability of $MoSi_2$ elements ensure that the reactor reaches the required temperature and maintains a uniform thermal field, promoting efficient decomposition and conversion of waste gas. W-type and straight rod $MoSi_2$ elements are suitable for large waste gas treatment furnaces, covering a wide heating area and supporting continuous waste gas treatment. U-type and spiral elements are suitable for small or laboratory furnaces, suitable for high-precision experiments or small-scale

电话/TEL：0086 592 512 9696
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sales@chinatungsten.com

treatment. The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance, adapting to corrosive gases (such as chlorides or sulfides) that may be present in the waste gas. During installation, the element is fixed by a high-purity alumina bracket, and the electrical connection uses a low-resistance clamp, which is matched with a proportional control power supply to achieve precise temperature control. The operation needs to control the atmosphere in the furnace to avoid the high reducing environment from damaging the SiO_2 film , and quickly pass through the "disease" temperature range to prevent oxidation damage. Maintenance includes regular inspection of the surface condition of the components and the cleanliness of the furnace, and removal of impurities that may affect the treatment effect. $MoSi_2$ components improve the decomposition efficiency and emission compliance rate of waste gas treatment, and are widely used in the chemical, power and environmental protection industries.

8.7.2 Catalyst regeneration

$MoSi_2$ heating elements are used in high-temperature regeneration furnaces and heat treatment furnaces in the catalyst regeneration process to restore the activity of catalysts, such as catalytic cracking catalysts in petrochemicals, selective catalytic reduction (SCR) catalysts in the environmental protection field, and industrial catalysts (such as precious metal catalysts).

After long-term use, the catalyst will be deactivated due to the deposition of carbonaceous materials, sulfides or other poisoning substances on the surface. The regeneration process needs to burn off these deposits at high temperatures while protecting the microstructure and active sites of the catalyst to restore its catalytic performance. The high power density and precise temperature control capabilities of $MoSi_2$ elements can provide a stable high-temperature environment to ensure the efficiency of the regeneration process and the recovery of catalyst performance.

U-shaped and spiral $MoSi_2$ elements are suitable for small regeneration furnaces, suitable for laboratory or small-scale regeneration processes, providing centralized heating to support high-precision temperature control, and meeting the needs of specific catalysts for strict temperature curves. W-shaped and straight rod $MoSi_2$ elements are suitable for large industrial regeneration furnaces, which can cover a wide heating area, provide a uniform heat field to support batch catalyst processing, and ensure the consistency of regeneration effects. The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating (such as SiC or Al_2O_3) enhances thermal shock resistance and corrosion resistance, and adapts to corrosive gases (such as sulfur-containing or chlorine-containing atmospheres) or frequent thermal cycles that may exist during the regeneration process.

During installation, the element is fixed by a high-purity alumina bracket , vertically suspended or horizontally supported to reduce mechanical stress, and the electrical connection uses a low-resistance clamp, and a proportional control power supply is used to achieve precise temperature control. The operation requires strict control of the furnace atmosphere to avoid the high reduction environment from destroying the SiO_2 film, and quickly pass through the "plague" temperature range to prevent the formation of non-protective oxides. Maintenance includes regular inspection of the surface state of the element, cold end connection and furnace cleanliness, and removal of impurities (such as metal oxides) that may affect the purity of the catalyst. $MoSi_2$ elements optimize the thermal field and process parameters to ensure the high efficiency and activity recovery effect of catalyst regeneration and extend the service life of the catalyst. They are widely used in the fields of petrochemicals, environmental protection and industrial catalysis.

8.7.3 Solid waste resource utilization

$MoSi_2$ heating elements are used in high-temperature pyrolysis furnaces, incinerators and sintering furnaces in solid waste recycling processes to treat industrial solid waste, urban garbage, hazardous waste and recover valuable materials (such as metals, ceramics or glass). Solid waste recycling requires high temperatures to decompose organic matter, volatilize harmful substances or sinter solid waste components to form reusable materials. The stable high-temperature performance and uniform thermal field distribution of $MoSi_2$ elements can meet these process requirements. W-type and straight rod $MoSi_2$ elements are suitable for large pyrolysis or incineration furnaces, covering a wide heating area, supporting continuous solid waste treatment, and ensuring the efficiency and consistency of the pyrolysis or sintering process. U-type and spiral $MoSi_2$ elements are suitable for small experimental furnaces or resource treatment of specific solid wastes, suitable for high-precision processes or R&D purposes, and provide centralized heating to optimize reaction conditions. The SiO_2 protective film provides reliable anti-oxidation protection in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance, adapting to the complex atmosphere that may be involved in solid waste treatment (such as chlorine, sulfur or heavy metal volatiles). During installation, the components are fixed by high-purity alumina brackets, and low-resistance clamps are used for electrical connections. The proportional control power supply is used to achieve precise temperature control to meet the control requirements of solid waste resource utilization for specific temperature curves. The operation requires the control of the atmosphere in the furnace to avoid the high reducing environment from damaging the SiO_2 film , and quickly pass through the "plague" temperature range to prevent oxidation damage. Maintenance includes regular inspection of the SiO_2 film , cold end connection and furnace cleanliness, and removal of impurities that may affect the quality of resource-based products. $MoSi_2$ components support the efficient decomposition, material recovery and resource utilization of solid waste by providing a reliable high-temperature environment, and are widely used in environmental protection, circular economy and resource recycling industries.

8.8 Application of $MoSi_2$ Heating Elements in Other Fields

Molybdenum disilicide ($MoSi_2$) heating elements have shown unique application value in high-tech fields such as aerospace and nuclear industry due to their excellent high-temperature performance, oxidation resistance and electrothermal stability. $MoSi_2$ elements can achieve excellent oxidation resistance through the SiO_2 protective film formed on the surface in an oxidizing atmosphere , which is suitable for long-term high-temperature operation. Its positive temperature coefficient resistivity characteristics ensure precise temperature control and uniform thermal field distribution, meeting the requirements of complex working conditions for high temperature, clean environment and thermal cycle resistance. U-shaped, W-shaped, spiral and straight rod $MoSi_2$ elements are customized according to equipment requirements. U-shaped and spiral types are suitable for small high-precision furnaces, and W-shaped and straight rod types are suitable for large tests or auxiliary equipment.

High-purity alumina brackets are used for installation to match the thermal expansion characteristics of $MoSi_2$ and reduce mechanical and thermal stress. Low-resistance clamps are used for electrical connections, and stable operation is achieved with proportional control power supply. The operation needs to quickly pass through the "disease" temperature range to avoid the formation of non-protective oxides. The surface coating (such as SiC or Al_2O_3) further enhances the thermal shock resistance and corrosion resistance and prolongs the life of the component. Regular maintenance includes checking the integrity of the SiO_2 film, the cold end connection status and the cleanliness of the furnace to ensure that there is no impurity contamination to meet the stringent requirements of the aerospace and nuclear industries. $MoSi_2$ elements provide reliable support for material testing and equipment operation in the field of high technology by optimizing thermal field design and operating parameters.

8.8.1 Aerospace Materials Testing

$MoSi_2$ heating elements are used in high-temperature test furnaces, thermal cycle test furnaces and environmental simulation equipment in aerospace material testing to test the performance of key aerospace materials such as high-temperature alloys, ceramic matrix composites, and carbon fiber composites. Aerospace materials need to undergo mechanical, thermal and chemical performance tests under extreme high temperature conditions to verify their reliability in engines, turbine blades or spacecraft thermal protection systems.

The high power density and precise temperature control capabilities of $MoSi_2$ elements can simulate these harsh environments. U-shaped and spiral $MoSi_2$ elements are suitable for small test furnaces, providing centralized heating to support high-precision testing, suitable for thermal exposure or thermal cycle experiments of small-sized samples. W-shaped and straight rod elements are suitable for large test furnaces, which can cover a wide heating area and provide a uniform thermal field to test large structural parts. The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance, adapting to oxidizing or trace corrosive atmospheres that may be involved in the test.

During installation, the element is fixed by a high-purity alumina bracket, and the electrical connection uses a low-resistance clamp, which is matched with a proportional control power supply to achieve precise temperature curve control. The operation requires strict control of the furnace atmosphere to avoid the reduction environment from damaging the SiO_2 film , and quickly pass through the "disease" temperature range to prevent oxidation damage. Maintenance includes regular inspection of the component surface condition, cold end connection and furnace cleanliness to ensure that no impurities affect the test results. $MoSi_2$ components support high-precision testing of aerospace materials by providing a stable high-temperature environment and reliable thermal cycle performance, providing key data for material development and certification.

8.8.2 Nuclear industry auxiliary equipment

$MoSi_2$ heating elements are used in high-temperature sintering furnaces, heat treatment furnaces and experimental reactors in auxiliary equipment of the nuclear industry for the preparation of nuclear fuel elements, reactor materials and the testing and processing of related high-temperature ceramics or alloys. The nuclear industry has extremely high requirements for the temperature control, cleanliness and long-term stability of equipment. The stable high-temperature performance and uniform thermal field distribution of $MoSi_2$ elements can meet these requirements. U-shaped and spiral $MoSi_2$ elements are suitable for small experimental furnaces, suitable for the sintering and heat treatment of nuclear fuel particles or small reactor materials, and provide high-precision temperature control to ensure material performance. W-shaped and straight rod elements are suitable for large auxiliary equipment, such as nuclear fuel rod sintering furnaces or reactor component heat treatment furnaces, providing large-area uniform heating to support mass production.

The SiO_2 protective film and surface coating ensure that the components can operate for a long time in an oxidizing atmosphere or a slightly corrosive environment, and the thermal shock resistance can adapt to frequent thermal cycles. High-purity alumina brackets are used for installation, and proportional control power is used for electrical connections to achieve precise temperature control to meet the nuclear industry's requirements for strict process parameters. The operation requires the control of the furnace atmosphere to avoid the high reducing environment from damaging the SiO_2 film , and quickly pass through the "plague" temperature range to prevent oxidation damage. Maintenance includes regular inspections of the SiO_2 film , cold end connections, and furnace cleanliness to ensure that there is no impurity contamination that affects the quality of nuclear materials. $MoSi_2$ elements support the preparation and performance verification of key materials in the nuclear industry by providing a reliable high-temperature environment, providing important guarantees for the safety and efficiency of nuclear energy technology.

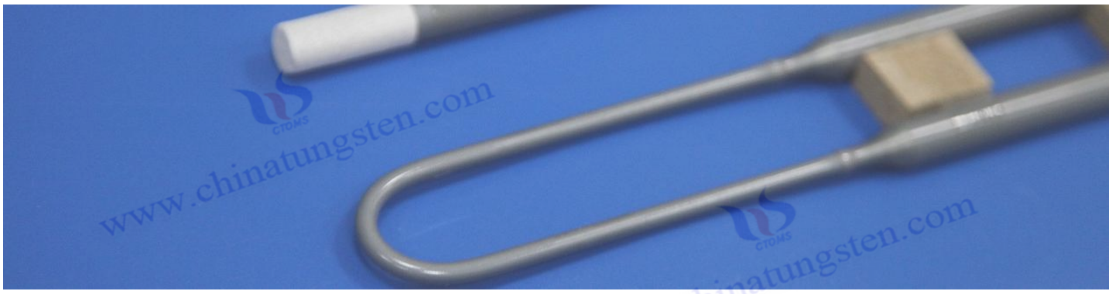
8.8.3 High temperature synthetic chemistry

$MoSi_2$ heating elements are used in reactors and experimental furnaces in high-temperature synthetic chemistry for the synthesis of high-temperature ceramics, intermetallic compounds, functional materials, and high-performance chemicals. High-temperature synthetic chemistry requires reactions to be carried out under strictly controlled temperature conditions to ensure the purity, crystal structure, and chemical properties of the products. The high power density and precise temperature control capabilities of $MoSi_2$ elements can provide a stable reaction environment. U-shaped and spiral $MoSi_2$ elements are suitable for small experimental furnaces, suitable for laboratory-scale chemical synthesis or new material research and development, providing centralized heating for high-precision temperature control. W-shaped and straight rod elements are suitable for large reactors, supporting industrial-scale chemical or material production, ensuring thermal field uniformity to reduce uneven reactions.

The SiO_2 protective film remains stable in an oxidizing atmosphere, and the surface coating (such as SiC or Al_2O_3) enhances thermal shock resistance and corrosion resistance, and adapts to corrosive gases or volatile products that may be present during the synthesis process. During installation, the components are fixed by high-purity alumina brackets, and low-resistance clamps are used for electrical connections, and a proportional control power supply is used to achieve precise temperature curve control. The operation requires controlling the atmosphere in the furnace to avoid the high reducing environment from destroying the SiO_2 film , and quickly passing through the "plague" temperature range to prevent oxidation damage. Maintenance includes regular inspection of the component surface state, cold end connection, and furnace cleanliness to ensure that there is no impurity contamination that affects the quality of the synthesized product. $MoSi_2$ components support efficient reactions and product quality in high-temperature synthetic chemistry by providing a reliable high-temperature environment, and are widely used in advanced materials and chemical industries.

8.8.4 $MoSi_2$ Rod Transformer

$MoSi_2$ heating elements are used as high-temperature heating sources in transformer-related applications for transformer material testing, insulation material heat treatment, and high-temperature processes during manufacturing. Transformer manufacturing involves high-temperature treatment of silicon steel sheets, insulating ceramics, or other high-temperature resistant materials. The stable high-temperature performance and uniform heat field distribution of $MoSi_2$ elements can meet these process requirements. U-shaped and spiral $MoSi_2$ elements are suitable for small heat treatment furnaces, suitable for local heating of transformer components or laboratory testing, and provide high-precision temperature control to optimize material properties. W-shaped and straight rod elements are suitable for large industrial furnaces for annealing silicon steel sheets or sintering of insulation materials, supporting mass production and ensuring thermal field uniformity. The SiO_2 protective film provides reliable anti-oxidation protection in an oxidizing atmosphere, and the surface coating enhances thermal shock resistance and corrosion resistance, adapting to the trace corrosive atmosphere that may be involved in transformer manufacturing. The installation adopts a high-purity alumina bracket, and the electrical connection uses a proportional control power supply to achieve precise temperature control and ensure the stability of process parameters. The operation needs to quickly pass through the "disease" temperature range to avoid oxidation damage. Maintenance includes regular inspection of SiO_2 film , cold end connection and furnace cleanliness to ensure that no impurities affect the material quality. $MoSi_2$ components provide a reliable high-temperature environment, support the heat treatment and performance optimization of key materials in transformer manufacturing, improve the efficiency and reliability of transformers, and are widely used in the field of power equipment manufacturing.



CTIA GROUP LTD Molybdenum Silicate Rod

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$MoSi_2$ Heating Element Introduction

1. Overview of $MoSi_2$ Heating Element

Molybdenum disilicide ($MoSi_2$) heating elements are high-performance ceramic electric heating materials widely used in industrial furnace applications. In high-temperature oxidizing atmospheres, $MoSi_2$ forms a dense silica (SiO_2) protective layer on its surface, which effectively prevents further oxidation. It exhibits excellent oxidation resistance and thermal stability, allowing stable operation under high temperatures for extended periods.

2. Features of $MoSi_2$ Heating Element

Low thermal expansion coefficient: Well-matched with common ceramic substrates, minimizing the risk of cracking caused by thermal stress.

Excellent oxidation resistance: Forms a dense SiO_2 protective film on the surface, effectively preventing material degradation from oxidation.

Extremely high working temperature: Capable of continuous operation up to 1700°C, and a maximum usage temperature of 1800°C in oxidizing atmospheres.

Good high-temperature electrical resistance characteristics: $MoSi_2$ exhibits relatively stable resistivity at high temperatures, with only a gradual increase in resistivity at elevated temperatures.

3. Specifications of $MoSi_2$ Heating Element

Model (d1/d2)	Hot End Diameter (d1)	Cold End Diameter (d2)	Hot Zone Length (Le)	Cold Zone Length (Lu)	Common Types
φ3/6	3 mm	6 mm	100–300 mm	150–250 mm	Straight / U-type
φ4/9	4 mm	9 mm	100–500 mm	200–300 mm	Straight / U-type
φ6/12	6 mm	12 mm	100–600 mm	200–350 mm	Straight / U-type / W-type
φ9/18	9 mm	18 mm	150–800 mm	250–400 mm	Straight / U-type / W-type
φ12/24	12 mm	24 mm	200–1000 mm	300–500 mm	Straight / U-type / W-type

4. Typical Applications of $MoSi_2$ Heating Element

High-temperature sintering furnaces in the ceramics and powder metallurgy industries
Heat treatment equipment for steel and non-ferrous metals
High-temperature laboratory furnaces
Diffusion, annealing, and oxidation processes in the semiconductor and photovoltaic industries

5. Purchasing Information

Email: sales@chinatungsten.com; Phone: +86 592 5129595; 592 5129696
Website: www.molybdenum.com.cn

Chapter 9 Comparison of $MoSi_2$ Heating Elements with Other Heating Materials

Molybdenum disilicide ($MoSi_2$) heating elements are widely used in high-temperature heating due to their excellent high-temperature performance, oxidation resistance and electrothermal stability. Compared with other common heating materials such as tungsten and silicon carbide (SiC), $MoSi_2$ elements have unique advantages in oxidation resistance, operating temperature range and process adaptability, but they also have certain limitations. This chapter compares the performance of $MoSi_2$ with tungsten heating elements and silicon carbide elements, analyzes their differences in cost, efficiency and application adaptability, and provides guidance for selecting suitable heating materials under different working conditions. $MoSi_2$ elements should be installed with high-purity alumina brackets to match thermal expansion characteristics, and low-resistance clamps should be used for electrical connections, with proportional control power supply to ensure stability. Operation needs to pass through the "plague" temperature range quickly to avoid the formation of non-protective oxides, and surface coatings (such as SiC or Al_2O_3) can enhance thermal shock resistance and corrosion resistance. Regular maintenance includes checking the integrity of the SiO_2 film and the status of the cold end connection to ensure that there is no impurity contamination.

9.1 Comparison with tungsten heating elements

$MoSi_2$ heating elements and tungsten heating elements each have their own advantages in high-temperature applications, but there are significant differences in applicable scenarios and performance characteristics. $MoSi_2$ elements can achieve excellent oxidation resistance through the SiO_2 protective film formed on the surface in an oxidizing atmosphere , which is suitable for long-term operation. The maximum operating temperature can reach 1850°C and is widely used in processes in oxidizing environments such as ceramic sintering, glass melting and semiconductor manufacturing. The positive temperature coefficient resistivity characteristics of $MoSi_2$ enable it to adaptively adjust power and provide stable temperature control, which is suitable for applications requiring high-precision temperature control. It has a moderate thermal expansion coefficient, good thermal shock resistance, can withstand frequent thermal cycles, and is suitable for U-shaped, W-shaped or spiral structural designs. The manufacturing process of $MoSi_2$ elements (such as powder metallurgy and isostatic pressing) allows flexible customization of shapes to meet complex furnace requirements. However, $MoSi_2$ is prone to generate non-protective oxides in the "plague" temperature range of 400-700°C, and rapid temperature rise and fall are required to avoid material degradation, and the operating temperature needs to be lowered in a reducing or vacuum environment to protect the SiO_2 film.

In contrast, tungsten heating elements are known for their extremely high melting point and excellent mechanical strength, making them suitable for ultra-high temperature applications (such as metal heat treatment in vacuum or inert atmosphere). Tungsten elements are very susceptible to oxidation in an oxidizing atmosphere and need to be operated under vacuum or inert gas protection, which limits their use in oxidizing environments. Tungsten has a low resistivity and changes less with temperature, making it suitable for scenarios requiring high power output, but its temperature control accuracy is lower than that of $MoSi_2$, requiring a more complex power control system. Tungsten elements have a low coefficient of thermal expansion and poor thermal shock resistance. Frequent thermal cycles may lead to brittle fracture, limiting their application under dynamic thermal loads. Tungsten elements have high manufacturing and processing costs, and are difficult to customize in shape. They are mostly wire or rod structures, which limits the design flexibility of complex furnace types. In addition, tungsten has a high density, resulting in a heavier element weight and more complex installation and support structure design.

The comparison between $MoSi_2$ and tungsten shows that $MoSi_2$ has better oxidation resistance and temperature control accuracy in oxidizing atmosphere, and is suitable for industries such as ceramics, glass and semiconductors, while tungsten is more suitable for ultra-high temperature applications (such as high-temperature alloy melting) in vacuum or inert atmosphere. The selection should be based on the process environment, temperature requirements and thermal cycle frequency. The long-term stability and flexibility of $MoSi_2$ in oxidizing environment make it more advantageous in most high-temperature furnaces.

9.2 Comparison with Silicon Carbide Components

$MoSi_2$ heating elements and silicon carbide (SiC) heating elements are both common choices in the field of high-temperature heating, but there are obvious differences in performance and application scenarios. $MoSi_2$ elements show excellent oxidation resistance in an oxidizing atmosphere through the surface SiO_2 protective film, and the maximum operating temperature can reach 1850°C, which is suitable for high-precision high-temperature processes such as ceramic sintering, glass melting and semiconductor epitaxial growth. Its positive temperature coefficient resistivity characteristics support adaptive power regulation, provide precise temperature control, and are suitable for applications that require a stable thermal field. $MoSi_2$ has a moderate thermal expansion coefficient, good thermal shock resistance, and can withstand frequent thermal cycles. U-shaped, W-shaped and spiral structures are suitable for a variety of furnace designs. The manufacturing process of $MoSi_2$ elements is flexible, and complex shapes can be produced through powder metallurgy and isostatic pressing to meet customized needs. However, $MoSi_2$ is prone to non-protective oxidation in the "plague" temperature range, requiring rapid temperature rise and fall, and the operating temperature needs to be lowered in a reducing or vacuum environment to protect the SiO_2 film.

SiC heating elements are known for their high hardness, wear resistance and chemical stability, and are widely used in industrial furnaces and medium and high temperature processes. SiC elements can also form a SiO_2 protective film in an oxidizing atmosphere, and have good oxidation resistance, but their maximum operating temperature is usually lower than that of $MoSi_2$, and are suitable for processes of 1300-1600°C. The resistivity of SiC varies more complexly with temperature, showing a negative temperature coefficient characteristic (resistance decreases at high temperatures), which may lead to unstable power output, and a precise control system is required to maintain temperature uniformity. SiC elements have a lower coefficient of thermal expansion and are slightly less resistant to thermal shock than $MoSi_2$. Frequent thermal cycles may cause microcracks, especially in large elements. The manufacturing process of SiC elements (such as reaction sintering or recrystallization) limits the complexity of the shape, which is usually rod-shaped or tubular, and the customization flexibility is lower than that of $MoSi_2$. In addition, SiC elements may suffer local corrosion in corrosive atmospheres containing sulfur or halogens, requiring additional surface protection measures.

Between $MoSi_2$ and SiC shows that $MoSi_2$ has advantages in higher temperature ranges and precise temperature control scenarios, and is suitable for high-tech industries such as semiconductor and special ceramic manufacturing, while SiC is more suitable for medium- and high-temperature, cost-sensitive industrial applications such as metal heat treatment and conventional ceramic sintering. The process temperature, atmosphere conditions, and thermal cycle requirements must be considered when selecting.

9.3 Analysis of heating element cost, efficiency and application suitability

The differences in cost, efficiency and application suitability of $MoSi_2$, tungsten and SiC heating elements directly affect their selection in different industries. The manufacturing cost of $MoSi_2$ elements is moderate, and the powder metallurgy and isostatic pressing processes are mature, allowing the production of complex shapes (such as U-shaped, W-shaped, spiral-shaped) to meet the needs of diversified furnace types. $MoSi_2$ has high operating efficiency, and its positive temperature coefficient resistivity characteristics support adaptive power regulation, reduce energy waste, and are suitable for scenarios that require precise temperature control and long-term operation, such as ceramic sintering, glass processing and semiconductor manufacturing. $MoSi_2$ has excellent oxidation resistance in an oxidizing atmosphere and low maintenance costs, but it needs to quickly pass through the "plague" temperature range to avoid oxidation damage, and surface coatings can further extend its life. $MoSi_2$ elements have a wide range of application adaptability and are suitable for high-temperature processes in an oxidizing atmosphere, but the temperature needs to be lowered in a reducing or vacuum environment, which limits its use in some ultra-high temperature metal treatments.

The manufacturing cost of tungsten heating elements is relatively high because of the difficulty in processing due to its high melting point material, and most of them are in the form of wires or rods, so it is expensive to customize complex shapes. Tungsten has higher operating efficiency in vacuum or inert atmosphere, which is suitable for ultra-high temperature applications (such as high-temperature alloy melting), but it is very easy to oxidize in an oxidizing atmosphere, requiring an additional atmosphere control system, which increases operating and maintenance costs. Tungsten elements have poor thermal shock resistance, and frequent thermal cycles may cause fractures. The maintenance cost is high. It is suitable for scenes with extremely high requirements for high temperature and vacuum environment, such as aerospace material testing, but the application range is narrow due to atmosphere restrictions.

SiC heating elements have relatively low manufacturing costs and a relatively simple reaction sintering process, making them suitable for large-scale production of rod or tubular elements. SiC's operating efficiency is high in the medium and high temperature range, but its negative temperature coefficient resistivity characteristics may lead to power instability, requiring a complex control system to maintain temperature uniformity, increasing operating costs. SiC elements have good oxidation resistance in an oxidizing atmosphere, but may experience local degradation in a corrosive atmosphere, and have moderate maintenance costs.

Chapter 10 Relevant Standards and Specifications for $MoSi_2$ Heating Elements

Molybdenum disilicide ($MoSi_2$) heating elements must follow strict standards and specifications to ensure product quality, performance stability and process safety. Globally, China's national standards, international standards and relevant standards of Europe, America, Japan and South Korea provide technical guidance for the manufacture and use of $MoSi_2$ heating elements. These standards cover the chemical composition, physical properties, manufacturing process, test methods and application specifications of the material. This chapter introduces in detail the Chinese national standards, international standards and relevant standards of Europe, America, Japan and South Korea for $MoSi_2$ heating elements, aiming to provide a reference for manufacturers, engineers and users. The standardization of $MoSi_2$ elements helps to unify product quality, improve interchangeability and promote global trade and technical cooperation.

10.1 Chinese National Standard for $MoSi_2$ Heating Elements

China's national standard (GB/T) has formulated a number of specifications for the production, performance testing and application of $MoSi_2$ heating elements, which are mainly managed by the National Technical Committee for Standardization of Nonferrous Metals (TC243) and other institutions. These standards ensure the performance stability and safety of $MoSi_2$ elements in high-temperature oxidizing environments, and are suitable for industries such as ceramic sintering, glass melting, and semiconductor manufacturing. Relevant standards include material chemical analysis, physical property testing, and technical requirements for industrial electric heating equipment. For example, the chemical composition standard of $MoSi_2$ elements specifies the content requirements and impurity control of major elements such as molybdenum and silicon to ensure oxidation resistance and electrothermal stability. The physical performance standards involve test methods for resistivity, thermal expansion coefficient, thermal shock resistance, and mechanical strength to ensure the reliability of the elements under high temperatures and frequent thermal cycles. In addition, the standards for industrial electric heating equipment put forward requirements for the installation, operation, and maintenance of $MoSi_2$ elements, such as using high-purity alumina brackets to match thermal expansion characteristics, quickly passing through the "plague" temperature range to avoid the formation of non-protective oxides, and regularly checking the integrity of the SiO_2 protective film. These standards are issued by the State Administration for Market Regulation and the National Administration of Standardization. Some of them refer to or adopt non-equivalent international standards (such as ISO related specifications) to adapt to China's industrial needs and keep pace with international standards.

10.2 International Standards for $MoSi_2$ Heating Elements

The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) have developed international standards related to $MoSi_2$ heating elements, focusing mainly on high-temperature materials, industrial electric heating equipment, and performance test methods. These standards provide a unified technical framework for the global production and application of $MoSi_2$ elements, covering material properties, manufacturing processes, and test specifications. For example, ISO standards may involve performance test methods for high-temperature ceramics or intermetallic compounds, including oxidation resistance, thermal conductivity, and resistivity tests, to ensure the long-term stability of $MoSi_2$ elements in oxidizing atmospheres. IEC standards focus on the technical requirements for industrial electric heating equipment, specifying the electrical connection, temperature control accuracy, and safety requirements of $MoSi_2$ elements, such as the use of low-resistance clamps and the configuration of proportional control power supplies. International standards also include test methods for thermal shock resistance and corrosion resistance of components in high-temperature environments, guiding manufacturers to optimize surface coatings (such as SiC or Al_2O_3) to extend service life. In addition, ISO and IEC standards emphasize the operating specifications of components in specific atmospheres (such as oxidizing or trace oxygen environments), requiring rapid passage through low temperature ranges to avoid "plague" oxidation. These standards promote the interchangeability and technical cooperation of $MoSi_2$ components in the global market and are widely used in the fields of ceramics, semiconductors and new energy materials preparation.

10.3 $MoSi_2$ Heating Element Standards in Europe, America, Japan, Korea and Other Countries

$MoSi_2$ heating element standards in Europe, America, Japan, South Korea and other countries are formulated by the standardization agencies of each country, combining local industrial needs and international standards, covering material properties, manufacturing processes and application specifications. In Europe, the European Committee for Standardization (CEN) and other institutions (such as the German Standards Institute DIN and the British Standards Institute BSI) have formulated standards related to high-temperature electric heating elements, involving the chemical composition, resistivity, thermal expansion coefficient and oxidation resistance test methods of $MoSi_2$ elements .

These standards emphasize the long-term stability of the components in an oxidizing atmosphere, specify the formation conditions and corrosion resistance requirements of the surface SiO_2 protective film, and are applicable to industries such as ceramic sintering and glass processing. The DIN standard may further refine the installation specifications of $MoSi_2$ elements , such as the use of high-purity alumina brackets and low-resistance design of electrical connections. The standards formulated by the American National Standards Institute (ANSI) focus on the performance and safety of industrial electric heating equipment, involving temperature control accuracy and thermal cycle performance testing of $MoSi_2$ elements to ensure their reliability in semiconductor and aerospace material testing.

Japan and South Korea have developed relevant specifications for $MoSi_2$ components through the Japanese Industrial Standards (JIS) and the Korean Agency for Technology and Standards (KATS) , focusing on applications in high-temperature ceramics and semiconductor manufacturing, and specifying the operating conditions of components in oxidizing and slightly corrosive atmospheres, such as rapid temperature rise and fall to avoid "plague" oxidation. These standards usually refer to the ISO and IEC framework, but are adjusted according to local industrial characteristics (such as Japan's precision manufacturing needs), emphasizing high-precision temperature control and long-life design of components. European, American, Japanese and Korean standards promote the application and trade of $MoSi_2$ components in the global market through unified test methods and quality requirements .

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$MoSi_2$ Heating Element Introduction

1. Overview of $MoSi_2$ Heating Element

Molybdenum disilicide ($MoSi_2$) heating elements are high-performance ceramic electric heating materials widely used in industrial furnace applications. In high-temperature oxidizing atmospheres, $MoSi_2$ forms a dense silica (SiO_2) protective layer on its surface, which effectively prevents further oxidation. It exhibits excellent oxidation resistance and thermal stability, allowing stable operation under high temperatures for extended periods.

2. Features of $MoSi_2$ Heating Element

Low thermal expansion coefficient: Well-matched with common ceramic substrates, minimizing the risk of cracking caused by thermal stress.

Excellent oxidation resistance: Forms a dense SiO_2 protective film on the surface, effectively preventing material degradation from oxidation.

Extremely high working temperature: Capable of continuous operation up to 1700°C, and a maximum usage temperature of 1800°C in oxidizing atmospheres.

Good high-temperature electrical resistance characteristics: $MoSi_2$ exhibits relatively stable resistivity at high temperatures, with only a gradual increase in resistivity at elevated temperatures.

3. Specifications of $MoSi_2$ Heating Element

Model (d1/d2)	Hot End Diameter (d1)	Cold End Diameter (d2)	Hot Zone Length (Le)	Cold Zone Length (Lu)	Common Types
φ3/6	3 mm	6 mm	100–300 mm	150–250 mm	Straight / U-type
φ4/9	4 mm	9 mm	100–500 mm	200–300 mm	Straight / U-type
φ6/12	6 mm	12 mm	100–600 mm	200–350 mm	Straight / U-type / W-type
φ9/18	9 mm	18 mm	150–800 mm	250–400 mm	Straight / U-type / W-type
φ12/24	12 mm	24 mm	200–1000 mm	300–500 mm	Straight / U-type / W-type

4. Typical Applications of $MoSi_2$ Heating Element

High-temperature sintering furnaces in the ceramics and powder metallurgy industries

Heat treatment equipment for steel and non-ferrous metals

High-temperature laboratory furnaces

Diffusion, annealing, and oxidation processes in the semiconductor and photovoltaic industries

5. Purchasing Information

Email: sales@chinatungsten.com; Phone: +86 592 5129595; 592 5129696

Website: www.molybdenum.com.cn

Appendix: Glossary of terms for $MoSi_2$ heating elements

common professional terms and their definitions in the field of molybdenum disilicide ($MoSi_2$) heating elements, which are intended to provide clear technical references for manufacturers, engineers and users. These terms cover aspects such as material properties, manufacturing processes, performance testing and application scenarios, helping to understand the characteristics and usage specifications of $MoSi_2$ heating elements.

the term	definition
Molybdenum disilicide ($MoSi_2$)	An intermetallic compound composed of molybdenum and silicon that has a high melting point, high oxidation resistance and excellent electrothermal properties and is often used in high-temperature heating elements.
SiO_2 protective film	of $MoSi_2$ in an oxidizing atmosphere to prevent further oxidation of the material and enhance high temperature stability.
Plague oxidation	$MoSi_2$ forms non-protective oxides (such as a mixture of MoO_3 and SiO_2) in the temperature range of 400-700°C , which causes the material to pulverize and deteriorate.
Positive Temperature Coefficient Resistivity (PTC)	$MoSi_2$ resistivity increasing with temperature supports adaptive power regulation and is suitable for precise temperature control applications.
Hot End	the $MoSi_2$ heating element is usually thinner and is responsible for generating the main heat. Common specifications include Φ6mm or Φ9mm.
Cold Junction	the $MoSi_2$ heating element is usually thicker (such as Φ12mm or Φ18mm) and doped with conductive materials to reduce the resistivity.
U-shaped element	A structure of $MoSi_2$ heating elements, in U shape, suitable for small furnaces or central heating, easy to install and replace.
W-type components	$MoSi_2$ heating element, W-shaped, suitable for large furnaces , providing a uniform heat field and good thermal shock resistance.
Spiral element	the $MoSi_2$ heating element is suitable for tube furnaces or high-precision heating, with concentrated heat field and precise temperature control.
Straight rod element	of $MoSi_2$ heating elements is suitable for uniform heating of large areas and is often used in continuous industrial furnaces.
Coefficient of thermal expansion	$MoSi_2$ material with temperature is about $8.1\times10^{-6}K^{-1}$, which affects the matching design of components and brackets .
Thermal shock resistance	$MoSi_2$ components to withstand rapid temperature changes without cracking is related to their fracture toughness and thermal expansion properties.
Fracture toughness	$MoSi_2$ materials to resist crack propagation is generally low, and the process needs to be optimized to reduce the risk of microcracks.

电话/TEL：0086 592 512 9696
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sales@chinatungsten.com

Thermal conductivity	$MoSi_2$ material to conduct heat affects the uniformity of the thermal field and the heating efficiency.
Power density	The heating power per unit area reflects the heating capacity of the $MoSi_2$ element and needs to be matched according to the furnace type and process.
Hot Pressing (HP)	A $MoSi_2$ component manufacturing process that uses high temperature and pressure molding to improve density and mechanical properties.
Pressureless sintering	A lower cost $MoSi_2$ component manufacturing process with slightly lower density, suitable for less demanding applications.
Self-propagating high temperature synthesis (SHS)	$MoSi_2$ by igniting Mo-Si mixed powder to induce an exothermic reaction is low-cost but has poor uniformity.
Isostatic Pressing	$MoSi_2$ blanks using uniform pressure is suitable for producing components with complex shapes.
Surface coating	A protective layer (such as SiC, Al_2O_3) applied to the $MoSi_2$ surface is used to enhance thermal shock resistance and corrosion resistance.
Plasma spraying	A technique for applying surface coatings by high temperature plasma spraying to form a dense coating suitable for industrial applications.
Chemical Vapor Deposition (CVD)	A technology for producing thin, uniform coatings with high adhesion for high-precision $MoSi_2$ components .
Resistivity test	for measuring the resistivity of $MoSi_2$ components usually uses the four-probe method to evaluate the electrothermal performance .
Antioxidant Test	to evaluate the stability of $MoSi_2$ components in high temperature oxidizing atmospheres, measuring SiO_2 film thickness and mass loss.
Thermal shock performance test	The experiment simulates rapid temperature rise and fall to test the crack resistance of $MoSi_2$ components and evaluates the changes in microcracks and mechanical strength.
Vickers hardness test	of $MoSi_2$ using a Vickers hardness tester reflects the wear resistance and mechanical properties.
Oxidizing atmosphere	Operating environment containing oxygen (oxygen partial pressure ≥ 0.2 atm), the main application condition of $MoSi_2$ components.
Reducing atmosphere	In an environment containing reducing gases such as hydrogen or carbon monoxide, the operating temperature of $MoSi_2$ needs to be lowered to avoid failure of the SiO_2 film .
Proportional control power supply	A power supply system that accurately regulates the power of $MoSi_2$ components , achieving stable temperature control with its positive temperature coefficient characteristics.
Low resistance gripper	for connecting $MoSi_2$ cold junction to power supply, with low contact resistance and ensuring electrical stability.
High purity alumina bracket	used to support $MoSi_2$ components , matching thermal expansion coefficient to reduce thermal stress.

Thermal field uniformity	The uniformity of temperature distribution in the furnace is affected by the layout and thermal conductivity of $MoSi_2$ components and requires optimized design .
Doping modification	of adding a small amount of elements (such as Y_2O_3 , Al_2O_3) to $MoSi_2$ to improve grain boundary strength or oxidation resistance.
Powder Metallurgy	$MoSi_2$ components by powder pressing and sintering , suitable for the production of complex shapes.
Quality loss rate	$MoSi_2$ components under high temperature oxidation reflects the anti-oxidation performance.
Grain size	The crystal grain size in the $MoSi_2$ microstructure affects the mechanical strength and thermal shock resistance .

illustrate:

This glossary is based on the manufacturing, testing and application practices of $MoSi_2$ heating elements, and refers to relevant literature and technical data. The definitions of terms are concise and accurate, and are applicable to the fields of ceramics, glass, semiconductors, new energy and environmental protection. Users can further supplement or adjust the terminology according to specific process requirements.

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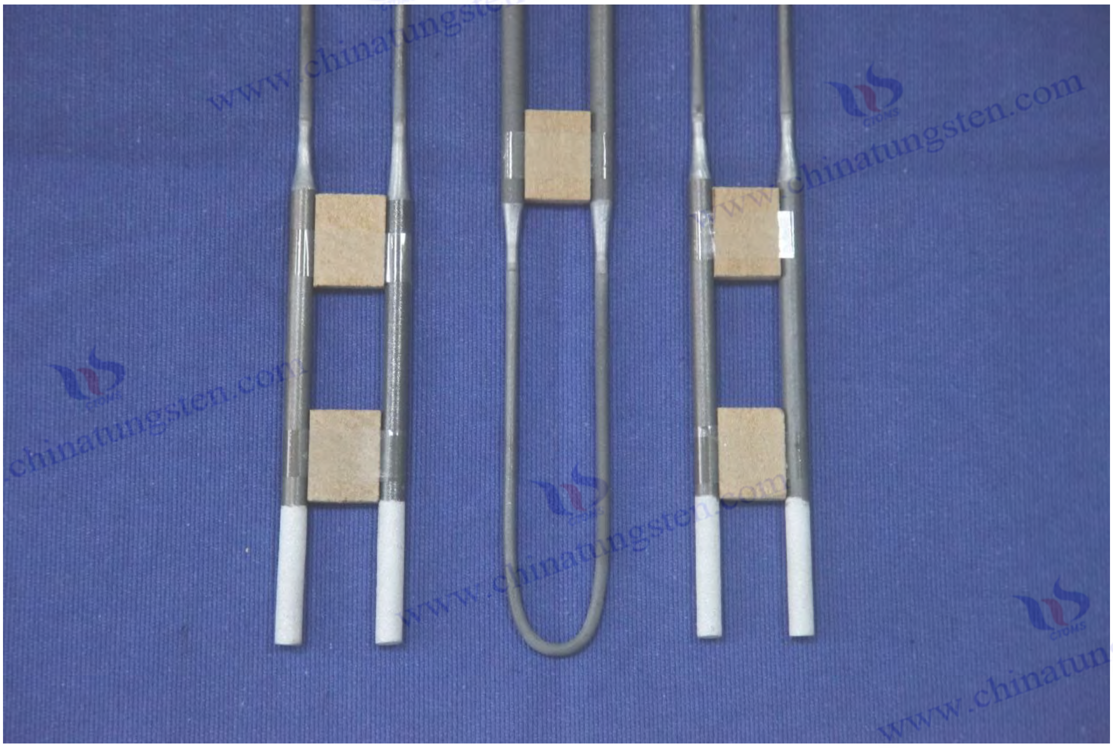

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