Encyclopedia of Electron Beam Tungsten Filaments

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

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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Electron Beam Tungsten Filaments Introduction

1. Overview of Electron Beam Tungsten Filaments

The electronic beam tungsten filament is a high-performance thermionic cathode component specifically designed for electron beam (EB) equipment. Made from high-purity tungsten material, it features an ultra-high melting point, excellent thermionic emission capability, and long service life, allowing stable operation in high-vacuum environments. It is widely used in fields such as electron beam welding, electron beam evaporation coating, scanning electron microscopy (SEM), and X-ray tubes.

2. Features of Electron Beam Tungsten Filaments

Ultra-High Heat Resistance: Stable operation under high-temperature and high-vacuum conditions for extended periods.

Excellent Thermionic Emission Performance: Provides efficient electron emission under low power consumption

High-Purity Material: W ≥ 99.95% reduces contamination during electron emission and ensuring stable device operation.

Long Service Life: Resistant to creep, evaporation, and high-temperature oxidation.

Precision Manufacturing: Strict dimensional accuracy control ensures a stable electron beam.

Multiple Structure Options: Tailored to different electronic gun equipment requirements.

3. Some Types of Electron Beam Tungsten Filaments

Mosquito Coil	Pull-type	U-shaped
		
Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm
U-shaped with Folding Tails	**Half Moon**	**Hook type**
		
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4. Purchasing Information

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Chapter 1 Introduction

1.1 Definition and Importance of Electron Beam Tungsten Filament

The Electron Beam Tungsten Filament is a cathode component with tungsten metal as the main material. It produces thermal electron emission through electric heating and is the core component of the electron gun. Electron guns use electric fields or magnetic fields to accelerate electrons to form high-energy electron beams. They are widely used in scanning electron microscopes (SEMs), transmission electron microscopes (TEMs), electron beam welding, X-ray tubes and other equipment. The importance of tungsten filaments stems from their excellent physical and chemical properties: high melting point (about 3422°C), low vapor pressure, high work function (about 4.5 eV), and excellent thermal stability and mechanical strength. These properties enable tungsten filaments to work stably in high-temperature and high-vacuum environments and provide reliable electron beams.

The tungsten filament in the electron gun is to heat it to 2000-2800°C by powering it on, exciting the electrons on the tungsten surface to overcome the work function and escape, forming an electron flow. These electrons are accelerated under the action of the electric field to generate a focused electron beam for imaging, processing or analysis. For example, in SEM, the emission stability and brightness of the tungsten filament directly affect the imaging resolution; in electron beam lithography, the life and consistency of the filament determine the processing accuracy of the nanoscale pattern. In addition, as a rare metal, the scarcity and high value of tungsten resources further highlight the strategic position of tungsten filaments in the global science and technology and industrial supply chain. According to information from Chinatungsten Online, the manufacturing technology of tungsten filaments is directly related to the performance and cost of electronic equipment, and is one of the key technologies in the high-tech field.

1.2 Historical Development and Technological Evolution

Tungsten filaments began in the late 19th century and is closely related to the rise of vacuum electronics. In 1878, Thomas Edison first used tungsten in incandescent filaments and discovered its high temperature tolerance and low evaporation rate, laying the foundation for tungsten in high-temperature applications. In the early 20th century, advances in vacuum tube technology led to the birth of electron guns, and tungsten became the preferred material for electron gun cathodes due to its high melting point and chemical stability. In the 1920s, tungsten filaments began to be used in early cathode ray tubes (CRTs), marking its widespread use in electronic devices.

In the 1950s, the advent of scanning electron microscopes placed higher demands on tungsten filaments, prompting researchers to optimize their microstructure and manufacturing process. In the 1960s, the introduction of doping technology became an important breakthrough. For example, the addition of elements such as potassium, aluminum, and silicon (tungsten knowledge) significantly improved the creep resistance and thermal electron emission efficiency of the filament. Entering the 21st century, advances in nanotechnology and precision manufacturing have further promoted the development of tungsten filament technology. For example, nanoscale grain control technology can optimize the mechanical properties of the filament, and surface coating technologies (such as oxide coating) can extend the life.

1.3 The Role of Electron Beam Tungsten Filament in Modern Technology

In modern technology, tungsten filaments are an indispensable component of electron guns and are widely used in scientific research, industrial manufacturing, medical treatment and emerging technology fields. Its main roles include:

Scientific research: In SEM and TEM, tungsten filaments provide high-brightness electron beams for observing nanoscale structures. For example, the emission stability of tungsten filaments directly affects the atomic-level resolution of TEM.

Industrial Manufacturing: Electron beam welding, cutting and lithography equipment rely on high-energy electron beams generated by tungsten filaments to achieve high-precision processing.

Medical applications: Tungsten filaments in X-ray tubes are used to generate the electron beams required for diagnostic imaging and are widely used in CT scanning and radiation therapy.

Emerging fields: Tungsten filaments are increasingly being used in 3D printing (electron beam melting), space propulsion systems (such as ion thrusters), and nanotechnology. For example, electron beam melting technology uses a high-energy electron beam generated by a tungsten filament to precisely melt metal powders to create complex structures.

Tungsten filaments directly affect equipment efficiency and precision. For example, in electron beam lithography, the emission consistency and lifetime of the filaments determine the quality of nanoscale patterns. With increasingly stringent requirements for environmental protection and sustainable development, green manufacturing and recycling of tungsten filaments have become a hot topic in the industry. Global companies are exploring waste tungsten recycling technologies and low-energy production processes to cope with resource shortages and environmental challenges.


CTIA GROUP LTD Electron Beam Tungsten Filament

Chapter 2: Basic Principles of Tungsten Filament in Electron Gun

2.1 Working Principle of Electron Gun

An electron gun is a device that accelerates an electron beam through an electric or magnetic field and is widely used in vacuum electronic devices. Its basic structure includes a cathode (usually a tungsten filament), an anode, and a control electrode (such as a grid). When working, the tungsten filament is heated to a high temperature (2000-2800°C) by electricity, releasing hot electrons; these electrons are accelerated by the electric field formed by the high voltage (several thousand volts to tens of kilovolts) applied by the anode to form a high-energy electron beam. The control electrode adjusts the intensity, shape, and focus of the electron beam to meet the needs of different applications.

The performance of an electron gun depends on the emission efficiency, beam stability and focusing accuracy of the filament. Tungsten filaments are the preferred cathode material for electron guns due to their high melting point, low vapor pressure and stable thermal electron emission characteristics. For example, in a scanning electron microscope, the electron gun needs to provide a high-brightness, narrow-beam electron beam, and the microstructure and surface state of the tungsten filament directly affect these parameters. According to data from Chinatungsten Online, modern electron gun designs can focus the electron beam to the sub-nanometer level by optimizing the filament geometry and electrode configuration.

2.2 Physical and chemical basis of tungsten filament as cathode material

Tungsten as a cathode material lies in its unique physical and chemical properties:

High melting point: The melting point of tungsten is 3422°C, which can withstand the high

temperature environment when the electron gun is working.
Low vapor pressure: Tungsten has a low evaporation rate at high temperatures, reducing filament loss and vacuum system contamination.
High work function: The work function of tungsten is about 4.5 eV, which is suitable for thermionic emission and provides a stable electron flow.
Chemical stability: Tungsten resists oxidation and corrosion in a vacuum environment and is suitable for long-term use.

Tungsten's body-centered cubic crystal structure gives it excellent mechanical strength and thermal stability. The addition of doping elements (such as potassium, aluminum, and silicon) can further optimize the performance, for example, reducing the work function or improving creep resistance. According to data from Chinatungsten Online, the emission efficiency of tungsten- doped filaments can be increased by 10-20%, significantly improving the performance of electron guns. In addition, tungsten surface morphology and cleanliness are critical to emission performance, and tiny impurities or oxide layers can significantly reduce emission efficiency.

2.3 Thermionic Emission Mechanism

Tungsten filament in electron gun is thermionic emission. When tungsten filament is heated to high temperature, the free electrons inside can overcome the potential barrier (called work function) formed on the surface of the material due to sufficient thermal energy, and then escape into the vacuum to form an electron flow.

According to the Richardson -Dushman equation , the relationship between the current density J of thermal electron emission and the temperature TT and the material work function φφ can be expressed as:

$$J = AT^2 e^{-\frac{\phi}{kT}}$$

In:
J: Electron emission current density (A/cm^2)
A : Richardson constant (usually about 120 $A/cm^2/K^2$)
T: Tungsten filament surface temperature (K)
ϕ : electronic work function of the material (eV)
k: Boltzmann constant (8.617×10^{-5} eV /K)

For tungsten , its work function is about 4.5–4.6 eV. Although it is not the lowest, due to its high melting point, it can withstand operating temperatures above 2000°C, making its thermal electron emission efficiency sufficient to meet the needs of electron guns.

The characteristic of thermal electron emission is that the electron current density increases rapidly with the exponential relationship of temperature. Therefore, the design of the electron gun must accurately control the heating current of the tungsten filament to obtain the required electron beam intensity while avoiding filament loss or breakage due to overheating.

In practical applications, the surface state of the filament has a significant impact on the emission performance. For example, surface oxides or impurities will increase the work function and reduce the emission efficiency; microscopic morphology (such as grain orientation and surface roughness) affects the electron escape efficiency. Therefore, chemical cleaning, polishing and surface coating techniques are often used in filament production to optimize performance.

2.4 Comparison of tungsten filaments and alternative materials

Although tungsten filaments have excellent performance, their high work function and limited lifetime have prompted researchers to explore alternative materials. Here is a comparison of tungsten filaments with common alternative materials:

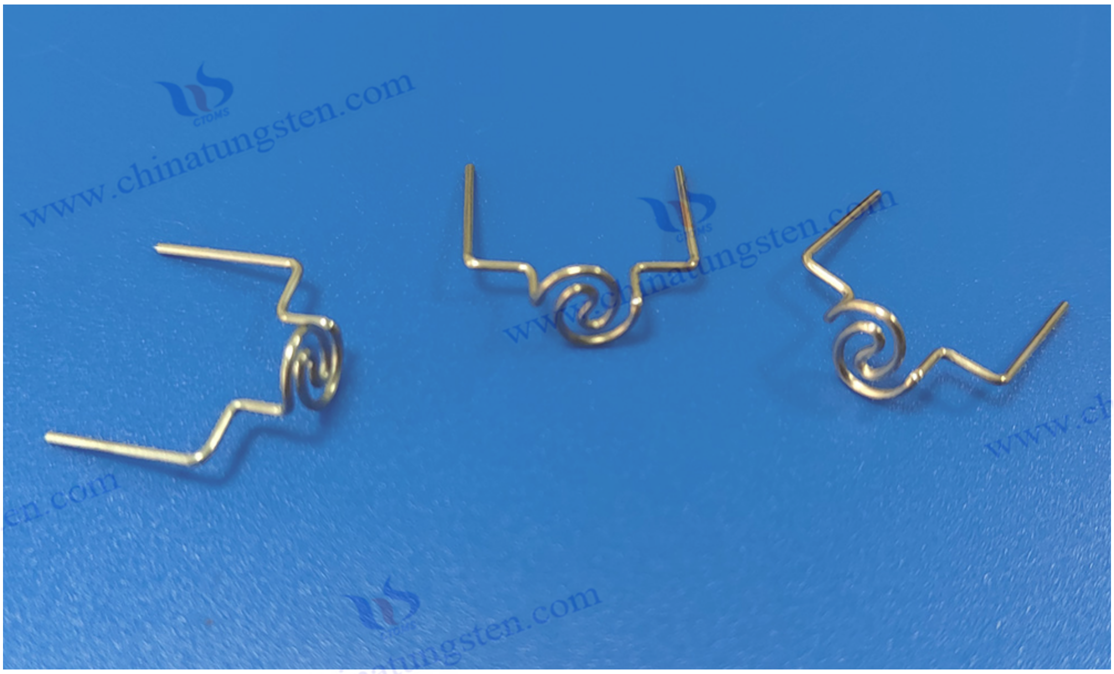
Lanthanum tungsten (LaB6): It has a low work function (about 2.7 eV) and high emission efficiency, making it suitable for high-brightness applications, but it has strict requirements on vacuum and is easily contaminated by oxygen.

Carbon nanotubes (CNTs): They have field emission properties, do not require heating, and are suitable for miniaturized applications, but their manufacturing costs are high and their stability needs further verification.

Oxide cathode: high emission efficiency and low operating temperature (about 1000°C), but poor mechanical strength and not suitable for high-power electron guns.

Tungsten-based composite materials: such as tungsten materials doped with oxides or carbides, have both high emission efficiency and long life, but the process is complex and the cost is high.

Tungsten filament make it dominate the high-power and long-life electron gun. However, under the demand for miniaturization and low power consumption, new materials such as carbon nanotubes and nanostructured tungsten are becoming research hotspots.



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Chapter 3: Preparation and production process of Electron Beam Tungsten Filament

Electron Beam Tungsten Filament is a key link to ensure its high performance and reliability, covering the entire process from raw material selection to final forming. This chapter discusses in detail the raw material preparation, metallurgical process, forming processing, production equipment, quality control, etc., combining global advanced technology and industry practices, and deeply analyzing the technical details and challenges of each step.

3.1 Selection and preparation of raw materials for Electron Beam Tungsten Filament

The quality of raw materials directly determines the performance of tungsten filaments, which involves the purification of tungsten metal, the characteristics of tungsten powder, the selection of doping materials and strict quality control.

3.1.1 Source and purification of tungsten metal

Tungsten metal is mainly extracted from wolframite (FeMnWO4) and scheelite (CaWO4), with global reserves mainly concentrated in China (about 60%), Russia, Australia and Canada. Wolframite is mainly due to its high tungsten content and easy separation characteristics, while scheelite requires a more complex purification process due to the associated calcium. The mining process includes open-pit mining or underground mining, followed by separation of tungsten concentrate through crushing, grinding and gravity separation (such as shaking table, spiral concentrator).

Tungsten purification process is divided into two stages: physical beneficiation and chemical smelting. Physical beneficiation further improves the purity of tungsten concentrate through flotation, magnetic separation and gravity separation, and the typical WO3 content needs to reach 65-70%. Chemical smelting converts tungsten concentrate into ammonium paratungstate or tungstic acid . The specific process includes:

Tungsten concentrate is leached with sodium hydroxide or sodium carbonate solution to form sodium tungstate solution.

Ion exchange or solvent extraction: removes impurities (such as silicon, phosphorus, arsenic) to produce high-purity APT.

Calcination and reduction: APT is calcined at 800-1000°C to generate tungsten trioxide , and then reduced to tungsten powder in a hydrogen atmosphere at a temperature of 700-900°C.

During the purification process, impurity control is crucial. Metal impurities such as iron, copper, and sulfur must be less than 50 ppm, and non-metallic impurities such as oxygen and carbon must be less than 100 ppm. High-purity tungsten powder (99.95%) is used in high-end electron gun filaments, which can significantly improve emission efficiency and life.

3.1.2 Particle size and purity requirements of tungsten powder

tungsten powder are key factors affecting the density of sintered blanks and the microstructure of filaments. The Electron Beam Tungsten Filament requires the tungsten powder to have uniform particle size, typically in the range of 1-10 microns, and the standard deviation of the particle size distribution to be controlled within ±0.5 microns. The fine and uniform particle size helps to form a dense sintered body with reduced porosity (target is less than 2%). Too large a particle size may result in uneven sintering, while too small a particle size may increase the difficulty of pressing.

In terms of purity, the content of metal impurities (such as iron, nickel, and molybdenum) in tungsten powder must be less than 30 ppm, and non-metallic impurities (such as oxygen, nitrogen, and carbon) must be less than 80 ppm. Ultra-high purity tungsten powder (5N grade, 99.999%) is in increasing demand in high-end applications, such as filament manufacturing for high-resolution SEM. Detection methods include:

Particle size analysis: A laser particle size analyzer (such as the Malvern Mastersizer) measures particle size distribution with an accuracy of ±0.1 micron.

Purity detection: Inductively coupled plasma mass spectrometry (ICP -MS) is used to analyze impurity content, with a detection limit as low as ppb level.

Microstructure observation: Scanning electron microscopy (SEM) was used to examine the powder morphology to ensure that there were no agglomerates or abnormal particles.

3.1.3 Selection of additives and doping materials (such as potassium, aluminum, silicon, etc.)

Doping is the core technology to optimize the performance of tungsten filaments. It improves its high temperature performance, emission efficiency and creep resistance by adding trace elements. Commonly used doping elements include:

Potassium (K): added in the form of potassium oxide (K_2O), with a content of 0.01-0.05 wt %. Potassium forms tiny bubbles during sintering, inhibits grain growth, and enhances high-temperature creep resistance.

Aluminum (Al): Added in the form of aluminum oxide (Al_2O_3) at 0.005-0.02 wt %. Aluminum reduces the work function (from 4.5 eV to about 4.3 eV) and improves the thermal electron emission efficiency.

Silicon (Si): Added in the form of silicon dioxide (SiO_2) at a content of 0.01-0.03 wt %. Silicon enhances high temperature strength and reduces surface oxidation.

Other elements: such as rhenium (Re, 0.1-1 wt %) is used to improve ductility, and yttrium oxide (Y_2O_3) is used to enhance emission properties.

The addition of doping elements needs to be uniformly distributed through wet mixing or mechanical alloying. Excessive doping may lead to abnormal grain growth or filament embrittlement. For example, potassium content exceeding 0.1 wt % will reduce mechanical strength.

3.1.4 Raw materials testing and quality control

Raw material testing covers chemical composition, particle size distribution, morphology and trace impurity analysis. Commonly used equipment includes:

X-ray fluorescence spectrometer (XRF): Rapidly analyze the chemical composition of tungsten powder and doping elements with an accuracy of ±0.01 wt%.

Scanning electron microscopy (SEM): observe powder morphology and detect agglomerated or irregular particles.

Transmission Electron Microscopy (TEM): Analyze nanoscale structures and evaluate the distribution of doping elements.

ICP -MS: Detect trace impurities with a sensitivity of ppb level.

Quality control follows ISO 9001 standards and establishes a full traceability system from raw material storage to production. Each batch of tungsten powder must pass at least three rounds of independent testing, and the pass rate must reach more than 99.9%. Unqualified raw materials are re-purified or discarded to avoid affecting subsequent processes.

3.2 Electron Beam Tungsten Filament Metallurgy

The metallurgical process transforms tungsten powder into high-performance tungsten filament, involving steps such as pressing, sintering, forging, drawing and annealing. Each step needs to be precisely controlled to ensure the microstructure and performance of the filament.

3.2.1 Tungsten Powder Pressing and Sintering

3.2.1.1 Pressing process parameters

Tungsten powder pressing is to put tungsten powder into a mold and press it into a blank through a hydraulic press or an isostatic press. The process parameters include:

Pressure: 100-300 MPa, typical value is 200 MPa. Too high pressure may cause die wear, too low pressure will affect the density of the billet .

Holding time: 10-30 seconds to ensure that the powder particles are fully combined.

Mould material: Tungsten carbide (www.tungsten-carbide-powder.com) or high strength steel , inner wall polished to Ra 0.1 micron to reduce adhesion.

Binder: Add 0.5-2 wt % polyvinyl alcohol (PVA) or paraffin to improve the strength of the blank, which needs to be completely removed at the beginning of sintering.

The relative density of the pressed blank must reach 60-70%, and the porosity must be controlled within 30%. CIP technology can further improve the density uniformity and is suitable for high-performance filament manufacturing.

3.2.1.2 Sintering furnace type and temperature control

Sintering is the process of densifying the pressed billet at high temperature, with the goal of reducing the porosity to less than 2% and forming a uniform grain structure. Common sintering furnaces include:

Resistance heating furnace: suitable for small batch production, temperature range 1800-2800°C.

Induction heating furnace: suitable for large-scale production, high heating rate and good uniformity.

Microwave sintering furnace: an emerging technology that achieves rapid densification through microwave heating, reducing energy consumption by 20-30%.

The sintering process is divided into three stages:

Low temperature stage (800-1200°C): removes binders and volatile impurities, lasting 30-60 minutes.

Medium temperature stage (1500-2000°C): Promotes grain bonding and pores begin to close, lasting 1-2 hours.

High temperature stage (2500-2800°C): achieves full densification, lasts 30-90 minutes.

The sintering atmosphere is high-purity hydrogen (purity 99.999%) or vacuum (10^-4 Pa) to prevent oxidation. The temperature control accuracy must reach ±5°C. Too high a temperature will cause abnormal grain growth, while too low a temperature will affect the density.

3.2.2 Forging and drawing of tungsten rods

3.2.2.1 Hot forging and cold forging technology

The sintered tungsten billet is processed into tungsten rods by forging to improve the internal structure and density. Forging is divided into hot forging and cold forging:

Hot forging: It is carried out at 1500-1800°C, using a rotary forging machine or a hydraulic forging machine. The deformation amount is controlled at 10-20% each time, and the total deformation rate reaches 50-70%. Hot forging can eliminate sintering pores and increase the density to more than 99%.

Cold forging: It is carried out at room temperature and is suitable for final finishing. Cold forging improves surface finish and dimensional accuracy, but the deformation rate must be controlled (0.1-0.5 mm/s) to avoid cracks.
The forging equipment needs to be equipped with high-precision molds and temperature monitoring systems to ensure that the tungsten rod diameter tolerance is within ±0.05 mm.

3.2.2.2 Wire drawing die design and lubricant selection

The tungsten rod is processed into a 0.01-0.5 mm diameter wire through multiple drawing processes. The key elements of the wire drawing process include:

Mold material: tungsten carbide or polycrystalline diamond (PCD), mold aperture accuracy ±0.1 micron, surface roughness Ra 0.05 micron.

Drawing passes: 20-40, with a surface reduction rate of 10-15% for each pass and a total surface reduction rate of more than 99%.

Lubricant: Graphite emulsion, molybdenum -based lubricant or nano-diamond suspension, reducing the friction coefficient to below 0.1.

Drawing speed: 0.5-5 m/s, needs to be adjusted dynamically according to wire diameter and mold status.

During the wire drawing process, the surface temperature of the tungsten wire can reach 300-500°C, and the heat accumulation needs to be controlled by a cooling system (such as water cooling or air cooling). The wire drawing machine is equipped with a tension sensor and a laser diameter gauge to monitor the wire diameter deviation (±0.5 microns) in real time.

3.2.3 Annealing and grain control of tungsten wire

3.2.3.1 Annealing temperature and atmosphere

Annealing is used to eliminate internal stress during the drawing process and optimize the grain structure and ductility of the tungsten wire. Annealing process parameters include:

Temperature: 1200-1600°C, typical value is 1400°C. Low temperature annealing (1200°C) is suitable for thin wires, high temperature annealing (1600°C) is used for thick wires.

Time: 10-60 seconds, short annealing time to avoid excessive grain growth.

Atmosphere: High purity hydrogen (99.999%) or inert gas (such as argon) to prevent oxidation.

Equipment: Continuous annealing furnace or vacuum annealing furnace, temperature control accuracy ±3°C.

During the annealing process, the tungsten wire is heated by resistance heating or induction heating, and local overheating must be avoided.

3.2.3.2 Effect of grain size on performance

Grain size directly affects the mechanical strength, ductility and thermal electron emission performance of tungsten wire. The ideal grain size is 1-5 microns:

Too large grains (>10 microns): reduce tensile strength and increase high temperature creep.

Too small grains (<1 micron): increase brittleness and reduce ductility.

Grain control is achieved through doping and annealing processes. Potassium doping forms tiny bubbles, hindering grain boundary migration and maintaining fine grains; precise control of annealing temperature and time avoids secondary recrystallization. Scanning electron microscopy and electron backscatter diffraction (EBSD) are used to analyze grain size and orientation to ensure the formation of fibrous structures.

3.3 Electron Beam Tungsten Filament forming and processing

Forming and machining is the process of processing tungsten filaments into specific geometric shapes (such as spirals or cones) to ensure the emission performance and mechanical stability of the filament in the electron gun.

3.3.1 Winding and forming of tungsten wire

3.3.1.1 Single helix, double helix and complex geometric designs

The geometry of the tungsten filament directly affects the brightness and focusing performance of the electron beam. Common designs include:

Single helical filament: suitable for low power electron guns (such as small SEM).

Double helix filament: Two tungsten filaments are wound in parallel to increase the emission area, suitable for high brightness applications (such as TEM).

Complex geometric designs: such as tapered spirals, multi-segment spirals or flat spirals, for special electron guns, e.g. in high-resolution lithography equipment.

The following parameters should be considered for spiral design:

Spiral diameter: 0.5-2.0 mm.

Spacing uniformity: Ensures emission uniformity.

Helix angle: 30-60°, affects the focusing characteristics of the electron beam.

The complex geometric design is optimized through computer-aided design (CAD) and finite element analysis (FEA) to ensure thermal distribution and mechanical stability.

3.3.1.2 Automation and precision of molding equipment

The winding equipment adopts a CNC system, equipped with a high-precision servo motor and a laser rangefinder. Key technologies include:

Servo control: Winding speed 0.1-10 rpm, accuracy ±0.01 rpm.

Laser ranging: real-time monitoring of spiral diameter and pitch, accuracy of ±1 micron.

Tension control: 0.1-5 N, to prevent the tungsten wire from deformation or breakage.

The automated winding machine supports multi-axis linkage, which enables rapid prototyping of complex geometric shapes. Modern equipment integrates machine vision systems to detect spiral defects (such as uneven spacing and surface scratches), reducing the scrap rate to less than 0.5%.

3.3.2 Surface treatment technology

3.3.2.1 Chemical cleaning and polishing

The surface of the tungsten wire needs to be free of oxides, oils and drawing residues to ensure the emission performance. The chemical cleaning process includes:

Pickling: Use a mixture of hydrofluoric acid (HF) and nitric acid (HNO_3) (ratio 1:3), soak for 10-30 seconds to remove surface oxides.

Alkaline cleaning: Use sodium hydroxide (NaOH) solution to neutralize acidic residues, and the cleaning time is 5-15 seconds.

Ultrasonic cleaning: carried out in deionized water, frequency 40 kHz, time 1-3 minutes, to remove tiny particles.

After cleaning, electrochemical polishing is performed using a mixed electrolyte of phosphoric acid (H_3PO_4) and sulfuric acid (H_2SO_4), a current density of 0.1-0.5 A/cm², and a polishing time of 10-20 seconds. After polishing, the surface roughness Ra drops to below 0.05 microns, significantly improving the emission uniformity.

3.3.2.2 Surface coating (e.g. oxide coating) process

Surface coatings reduce work function and improve emission efficiency and lifetime. Common coatings include yttrium oxide (Y_2O_3), zirconium oxide (ZrO_2) and thorium oxide (ThO_2). Coating processes include:

Chemical Vapor Deposition (CVD): Deposition of oxide coatings at 600-800°C with a thickness of

0.1-1 micron and a uniformity of ±0.01 micron.

Plasma spraying: suitable for thick coatings (1-5 microns), strong adhesion at high temperatures.

Sol-gel method: produces nanoscale coatings, suitable for high-precision filaments.

The coating needs to be firm to avoid peeling due to high temperature.

3.3.3 Filament cutting and shaping

Filament cutting uses laser cutting or EDM cutting with an accuracy of ±5 microns. Laser cutting uses pulsed laser (wavelength 1064 nm, power 10-50 W), cutting speed 0.1-1 mm/s, avoiding heat-affected zone. EDM cutting is suitable for complex shapes, and the electrode gap is controlled at 10-20 microns.

After cutting, the filament is shaped using a high-precision fixture and microscope to adjust the shape of the filament. The shaping equipment is equipped with a servo system with a positioning accuracy of ±2 microns to ensure that the spiral geometry meets the design requirements.

3.4 Electron Beam Tungsten Filament Production Equipment and Automation

Production equipment and automation technology are the key to improving filament consistency and efficiency, covering sintering furnaces, wire drawing machines, winding machines and intelligent production lines.

3.4.1 Overview of key production equipment

3.4.1.1 Sintering furnace

The sintering furnace needs to support high temperature (2800°C) and high vacuum (10^-5 Pa) environment. Modern sintering furnaces use the following technologies:

PLC control: multi-stage heating program, temperature deviation ±3°C.

Atmosphere system: high-purity hydrogen or argon, flow control accuracy ±0.1 L/min.

Cooling system: water cooling or air cooling, cooling rate 10-50°C/min.

Microwave sintering furnaces are an emerging trend, reducing energy consumption by 30% and shortening sintering time by 50%.

3.4.1.2 Wire drawing machine

The wire drawing machine is equipped with multi-pass dies and an automatic lubrication system. Key parameters include:

Number of molds: 20-40, aperture reduction rate 10-15%.

Drawing speed: 0.5-10 m/s, dynamically adjusted to avoid wire breakage.

Diameter measuring system: Laser diameter measuring instrument, accuracy ±0.5 micron.

High-speed wire drawing machines support continuous production, with a single drawing length of several thousand meters.

3.4.1.3 Wrapping machine

The winding machine adopts a six-axis CNC system to support complex spiral designs. Key technologies include:

Servo motor: speed accuracy ±0.01 rpm.

Laser monitoring: Real-time detection of spiral geometry with an accuracy of ±1 micron.

Tension control: 0.1-5 N, dynamically adjustable.

The automated winding machine can produce 150-200 spirals per minute with a scrap rate of less than 0.3%.

3.4.2 Automation and intelligence of production lines

The automated production line integrates the following technologies:

Sensor: monitors temperature, pressure, wire diameter and other parameters with an accuracy of ±0.1%.

Machine vision: Detect surface defects and geometric deviations with a recognition rate of 99.9%.

AI algorithms: Analyze production data, predict equipment failures and optimize process parameters.

Intelligent production lines connect devices through the Industrial Internet of Things (IIoT), and data is uploaded to the cloud in real time for analysis.

3.4.3 Environmental Control and Clean Room Requirements

Tungsten filament production must be carried out in an ISO Class 5 (Class 100) clean room. Environmental parameters include:

Temperature: 20±1°C, to avoid thermal expansion affecting accuracy.

Humidity: 40-60%, to prevent static electricity accumulation.

Air cleanliness: less than 100 0.5 micron particles per cubic meter.

The cleanroom is equipped with a high efficiency filter (HEPA) and a positive pressure system to prevent dust contamination. Air particle concentration is regularly tested to ensure compliance with ISO 14644-1 standards.

3.5 Quality Control and Inspection of Electron Beam Tungsten Filament

Quality control runs through the entire production process, covering online inspection, performance testing and failure analysis to ensure that the filament performance meets the requirements of the electron gun.

3.5.1 Online detection technology

3.5.1.1 Dimensional and geometrical accuracy inspection

Dimensional inspection uses a laser diameter gauge and optical microscope to measure the tungsten wire diameter, spiral pitch and geometric deviation:

Diameter: accuracy ± 0.1mm , deviation less than ± 1.0mm .

Spiral pitch: accuracy ± 2.0mm , ensuring emission uniformity.

Geometric deviation: measured by 3D scanner, the deviation is less than ± 0.5mm .

The online detection system collects 1,000 data points per second, provides real-time feedback to the control system, and automatically adjusts process parameters.

3.5.1.2 Surface defect detection

Surface defects (e.g. cracks, oxide residues, scratches) are identified by the following techniques:

Scanning electron microscope (SEM): Magnification 1000-10000 times, detect nanoscale defects.

X-ray non-destructive testing: Identification of internal cracks and pores, penetration depth 0.1-1 mm.

Machine vision: High-resolution cameras combined with AI algorithms, with a detection rate of 99.8%.

Defect detection covers 100% of products, and the scrap rate is controlled below 0.2%.

3.5.2 Performance Testing

3.5.2.1 Resistance and conductivity test

The resistance test uses the four-probe method to measure the resistivity (5.6 μΩ·cm, 20°C) and temperature coefficient (0.0045/°C) of the tungsten wire. The test conditions include:

Temperature range: 20-2800°C, simulating actual working environment.

Current accuracy: ±0.1 μA, ensuring measurement accuracy.

The conductivity test is carried out in a vacuum chamber to verify the electrical stability of the filament at high temperatures.

3.5.2.2 Thermal electron emission performance test

Thermionic emission tests are conducted in a high vacuum (10^-6 Pa) environment to measure the emission current density of the filament at 2000-2800°C. The test equipment includes:

Vacuum chamber: equipped with electron collector and voltage source.

Temperature monitoring: Infrared thermometer, accuracy ±5°C.

Current measurement: Picoammeter , accuracy ±0.1 μA/cm².

The test results must conform to the Richardson- Dushman equation, and the emission current density target is 1-5 A/cm².

3.5.3 Failure analysis and improvement measures

Failure analysis identifies the cause of filament breakage, evaporation or surface degradation. Common methods include:

SEM and energy dispersive spectrometer (EDS): Analyze fracture morphology and chemical composition, and identify grain boundary defects or impurities.

X-ray Tomography (CT): Detects internal cracks and pores with an accuracy of ±1 micron.

Thermogravimetric analysis (TGA): measures high temperature evaporation rate and assesses lifetime.

Improvements include optimizing the doping formula (such as increasing the potassium content), adjusting the sintering temperature (reducing it by 50°C) and strengthening the surface coating.

CTIA GROUP LTD Electron Beam Tungsten Filament

Chapter 4: Product Characteristics of Electron Beam Tungsten Filament

Electron Beam Tungsten Filaments directly determines their performance in high-precision electronic equipment, including scanning electron microscopes, electron beam welding equipment, and X-ray tubes. This chapter discusses in detail the physical and chemical properties, electrical and thermal properties, microstructure and performance relationships, life and reliability of tungsten filaments, and the Material Safety Data Sheet (MSDS) provided by CTIA GROUP LTD. Through in-depth analysis of these characteristics, the behavior of tungsten filaments under extreme conditions and their optimization direction are revealed .

4.1 Physical and chemical properties of Electron Beam Tungsten Filament

tungsten filaments are the basis for their use as cathode materials in electron guns, and determine their stability and functionality in high temperature and high vacuum environments.

4.1.1 Melting point and thermal stability of tungsten filament

Tungsten filaments are known for their extremely high melting point (3422°C), one of the highest melting points of metals found in nature. This property enables it to maintain its structural integrity at the operating temperatures of the electron gun (typically 2000-2800°C) without melting or significantly deforming. Tungsten's high melting point comes from its body-centered cubic (BCC) crystal structure, which has extremely strong metallic bonds between atoms.

Thermal stability is another key advantage of tungsten filaments, reflected in their extremely low vapor pressure. At 2800°C, the vapor pressure of tungsten is only 10^-7 Pa, which means that even at high temperatures for a long time, the evaporation rate of the material is extremely low. For example, at 2500°C, the mass loss rate of tungsten filament is about 0.01 mg/cm²·h, which is much lower than other cathode materials such as lanthanum tungsten (LaB6). This low evaporation characteristic reduces thinning of the filament diameter, extending service life while avoiding contamination within the vacuum system.

Another manifestation of thermal stability is the tungsten filament's tolerance to thermal shock. During the startup and shutdown of the electron gun, the filament undergoes rapid hot and cold cycles (from room temperature to 2500°C, with a heating rate of up to 100°C/s). Tungsten's high heat capacity (0.13 J/g·K) and excellent thermal conductivity (173 W/m·K) enable it to quickly disperse heat, reducing local overheating and thermal stress. Doping elements (such as potassium) further enhance thermal stability, inhibit grain growth by forming tiny bubbles, and reduce high-temperature creep rates. Actual tests have shown that potassium-doped tungsten filaments can operate continuously for more than 5000 hours at 2600°C with a mass loss of less than 5%.

4.1.2 Resistivity and temperature coefficient of tungsten filament

tungsten filaments is the core parameter of their electrical performance, which directly affects the heating efficiency and current stability. At 20°C, the resistivity of tungsten is 5.6 μΩ·cm, and as the temperature rises, the resistivity increases nonlinearly. At 2500°C, the resistivity can rise to 50-60 μΩ·cm, an increase of about 10 times. This change is due to the effect of temperature on electron scattering. At high temperatures, the lattice vibration is enhanced, hindering the movement of electrons.

TCR) of tungsten is about 0.0045/°C in the range of 20-1000°C, indicating that the resistivity increases linearly with temperature, but at higher temperatures (such as >2000°C), the TCR decreases slightly (about 0.0038/°C), reflecting slight changes in the crystal structure. The stability of the resistivity ensures that the filament has predictable electrical properties under dynamic temperature conditions. For example, in electron guns, the filament is usually heated by a constant current power supply (current 0.5-5 A), and the stable change of the resistivity allows precise control of the heating power (50-200 W) to avoid overheating or underheating.

Doping elements have a small effect on resistivity. For example, adding 0.01 wt % aluminum can reduce the resistivity by about 5% because aluminum atoms partially replace tungsten atoms, optimizing the electron conduction path. Surface treatments (such as oxide coatings) have a smaller effect on resistivity, but may slightly increase the surface resistance at high temperatures due to decomposition of the coating. In practical applications, the filament resistance is measured by the four-probe method with an accuracy of ±0.1 μΩ·cm to ensure batch-to-batch consistency.

4.1.3 Anti-oxidation and anti-corrosion properties of tungsten filament

Tungsten filaments exhibit excellent oxidation resistance in high vacuum environments (10^-6 Pa) because their surface is difficult to react with residual oxygen to form oxides. Under typical electron gun operating conditions (2500°C, vacuum 10^-7 Pa), the oxidation rate is almost zero, and the surface remains smooth and free of oxide accumulation. However, in non-ideal vacuum environments (such as 10^-4 Pa) or in air, tungsten easily reacts with oxygen at high temperatures to form tungsten trioxide, a yellow volatile compound. For example, in air at 1000°C, the tungsten surface oxidation rate is about 0.1 mg/cm²·min, resulting in rapid material loss.

The corrosion resistance enables tungsten filaments to withstand residual gases in electron guns, such as water vapor, nitrogen and trace hydrocarbons. Under high vacuum, the partial pressure of these gases is extremely low (<10^-8 Pa) and their effect on tungsten is negligible. However, at lower vacuum levels (such as 10^-5 Pa), water vapor may cause micro-corrosion on the surface, forming a thin layer of oxide and reducing the emission efficiency. Surface coatings such as yttria or zirconium oxide significantly enhance corrosion resistance by forming a protective layer that blocks the penetration of gas molecules. Tests show that yttrium oxide coating can reduce the oxidation rate by 60% and maintain no obvious degradation for 2000 hours under a vacuum of 10^-5 Pa.

Tungsten filaments to chemical corrosion are also reflected in their resistance to arc discharge products. In electron guns, arc discharge may produce plasma containing active ions (such as O^{2+}, N^{2+}). The high chemical stability of tungsten makes its surface less susceptible to damage by ion bombardment, maintaining long-term performance.

4.1.4 Mechanical strength and ductility of tungsten filament

tungsten filaments is an important property for them in high temperature and high stress environments. At room temperature, tungsten has a tensile strength of 800-1000 MPa and a yield strength of about 600 MPa. Even at 2500°C, the tensile strength remains at 300-500 MPa, which is much higher than other cathode materials such as nickel (<100 MPa). The high strength comes from tungsten's BCC crystal structure and low defect density, and doping elements further optimize the properties. For example, adding 0.05 wt % potassium can increase the tensile strength by 20% through grain boundary strengthening and reduce high temperature deformation.

Ductility is a key parameter of tungsten filaments during drawing and winding. Pure tungsten is brittle at room temperature, with an elongation at break of only 1-2%, but through doping (such as rhenium, 0.1-1 wt %) and annealing processes, the elongation at break can be increased to 5-10%. Rhenium doping reduces the energy barrier for dislocation movement and enhances plastic deformation capacity. Annealing (1200-1600°C, hydrogen atmosphere) eliminates drawing stress, forms a uniform fibrous grain structure, and further improves ductility. Actual tests show that the breakage rate of rhenium-doped tungsten wire during drawing is less than 0.1%, which is suitable for complex spiral forming.

The balance between mechanical strength and ductility is critical to the vibration resistance of the filament. In electron guns, the filament may be subjected to mechanical vibration (10-100 Hz) or thermal shock. The optimized tungsten filament showed excellent mechanical reliability with no cracks in 1000 vibration tests (amplitude 0.5 mm).

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Electron Beam Tungsten Filaments Introduction

1. Overview of Electron Beam Tungsten Filaments

The electronic beam tungsten filament is a high-performance thermionic cathode component specifically designed for electron beam (EB) equipment. Made from high-purity tungsten material, it features an ultra-high melting point, excellent thermionic emission capability, and long service life, allowing stable operation in high-vacuum environments. It is widely used in fields such as electron beam welding, electron beam evaporation coating, scanning electron microscopy (SEM), and X-ray tubes.

2. Features of Electron Beam Tungsten Filaments

Ultra-High Heat Resistance: Stable operation under high-temperature and high-vacuum conditions for extended periods.

Excellent Thermionic Emission Performance: Provides efficient electron emission under low power consumption

High-Purity Material: W ≥ 99.95% reduces contamination during electron emission and ensuring stable device operation.

Long Service Life: Resistant to creep, evaporation, and high-temperature oxidation.

Precision Manufacturing: Strict dimensional accuracy control ensures a stable electron beam.

Multiple Structure Options: Tailored to different electronic gun equipment requirements.

3. Some Types of Electron Beam Tungsten Filaments

Mosquito Coil	Pull-type	U-shaped
 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm
U-shaped with Folding Tails	**Half Moon**	**Hook type**
 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm

4. Purchasing Information

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

Website: www.tungsten.com.cn

4.2 Electrical and thermal characteristics of Electron Beam Tungsten Filament

The electrical and thermal properties determine the heating efficiency, electron emission performance and thermal management capabilities of the tungsten filament in the electron gun, and are the core of its functionality.

4.2.1 Thermionic Emission Efficiency of Tungsten Filament

Thermionic emission efficiency is the core indicator of tungsten filament as cathode material, which is determined by work function, surface state and operating temperature. The work function of pure tungsten is 4.5 eV, indicating that the energy required for electrons to escape from the surface is high. At 2500°C, the emission current density of tungsten filament is 1-5 A/cm², and the brightness is about 10^5-10^6 A/cm²· sr , which is suitable for most electron gun applications. The emission efficiency follows the Richardson- Dushman equation:

$$J = AT^2 e^{-\frac{\phi}{kT}}$$

Where (J) is the emission current density, (A) is the Richardson constant (about 120 A/cm²·K²), (T) is the absolute temperature, (\phi) is the work function, and (k) is the Boltzmann constant (8.617×10^-5 eV/K). The equation shows that the emission efficiency increases exponentially with temperature, but high temperature accelerates evaporation, and a balance needs to be optimized.

Doping and surface coatings significantly increase emission efficiency. Adding 0.01 wt % aluminum can reduce the work function to 4.3 eV and increase the emission current density by 15-20%. Yttrium oxide (Y2O3) coating (thickness 0.1-1 micron) further reduces the work function to 4.2 eV and increases the emission efficiency by 30%, reaching 8 A/cm² at 2600°C. Surface cleanliness has a significant impact on emission performance, and trace oxide or carbon contamination can increase the work function by 0.1-0.2 eV and reduce efficiency by 10%. Chemical cleaning (hydrofluoric acid + nitric acid) and electrochemical polishing (Ra < 0.05 microns) ensure a pure surface and optimize emission uniformity.

In practical applications, the emission efficiency is measured by a vacuum test rig equipped with an electron collector and a picoammeter with an accuracy of ±0.1 µA/cm². Doped and coated filaments can provide a brightness of 10^7 A/cm²· sr in high-resolution SEM , meeting the needs of sub-nanometer imaging.

4.2.2 Operating temperature range of tungsten filament

Tungsten filaments is 2000-2800°C, depending on the application scenario. Low-power devices (such as cathode ray tubes) use 2000-2200°C and an emission current of 0.1-1 mA; high-brightness devices (such as transmission electron microscopes) use 2600-2800 °C and an emission current of 5-10 mA. The temperature selection needs to balance the emission efficiency and life. For every 100°C increase in temperature, the emission current density increases by about 2 times, but the evaporation rate increases by 3-4 times, and the life is shortened by 30-50%.

Temperature control is achieved through a constant current or constant voltage power supply, with a typical heating power of 50-200 W. An infrared thermometer (accuracy ±5°C) or thermocouple monitors the filament temperature in real time to avoid local overheating. The filament geometry design (such as double helix) increases the heat dissipation area, reduces temperature gradients, and reduces thermal stress. For example, the temperature uniformity of a double helix filament is 20% higher than that of a single helix, and local hot spots are reduced by 50%.

Under extreme conditions (such as nuclear fusion devices), the filament may briefly reach over 3000°C, at which time special doping (such as rhenium) or coating (such as zirconium oxide) is required to maintain performance. Tests have shown that rhenium- doped filaments can operate at 2900°C for 100 hours with less than 10% mass loss.

4.2.3 Thermal expansion and thermal fatigue performance of tungsten filament

The thermal expansion coefficient of tungsten is 4.5×10^-6/°C (20-1000°C), which is relatively low among metals, indicating that it has little deformation at high temperatures. At 2500°C, the thermal expansion coefficient increases slightly to 5.0×10^-6/°C, but still maintains excellent dimensional stability. Low thermal expansion reduces the mechanical stress of the filament during hot and cold cycles, which is particularly suitable for the frequent startup and shutdown of electron guns. For example, the length of the filament changes by only 1.1% when it rises from 20°C to 2500°C, and the effect on the spiral geometry is negligible.

Thermal fatigue performance reflects the durability of the filament in repeated heating-cooling cycles. In 1000 hot-cold cycle tests (20-2500°C, heating rate 100°C/s), the crack incidence rate of potassium-doped tungsten filaments was less than 1%, which is much better than pure tungsten (crack rate 5%). The improvement in thermal fatigue is due to the following factors:

Grain structure optimization: Fine grains (1-5 microns) disperse stress through grain boundaries and reduce crack propagation.

Doping strengthening: Potassium bubbles and rhenium doping increase grain boundary strength and inhibit microcrack formation.

Surface treatment: Polishing and coating reduce surface stress concentration and reduce fatigue starting points.

Thermal fatigue testing uses a high-temperature cycle furnace and scanning electron microscope (SEM) to analyze crack morphology, combined with finite element simulation to predict stress distribution and optimize filament design.

4.2.4 Arc stability of tungsten filament

Arc stability refers to the ability of the filament to avoid abnormal discharge (such as arc breakdown) at high voltage (5-20 kV), which is the key to the quality of electron gun beam. Arcing can be caused by surface defects, residual gas, or electric field inhomogeneity, resulting in electron beam jitter or equipment damage. The high chemical stability and surface finish (Ra < 0.05 microns) of the tungsten filament significantly reduce the risk of arcing.

Vacuum degree is an important factor in arc stability. At 10^-7 Pa, the residual gas partial pressure is extremely low, and the probability of arc occurrence is less than 0.01%. At lower vacuum degrees (such as 10^-5 Pa), water vapor or oxygen may cause micro-discharges. Surface coatings (such as zirconium oxide) reduce the risk of discharge by 50% by increasing the dielectric strength. The filament geometry design also affects stability. The double helix filament reduces the arc occurrence rate by 30% through uniform electric field distribution.

The arc stability test was conducted in a high vacuum chamber, with a voltage of 10-20 kV applied and the discharge current monitored (<1 μA was considered acceptable). The test results showed that the filament with optimized surface treatment could run continuously for 1000 hours at 15 kV without arcing, meeting the requirements of high-precision electron guns.

4.3 Relationship between the microstructure and performance of Electron Beam Tungsten Filament

The microstructure of tungsten filaments, including grain structure, doping element distribution and surface morphology, directly affects their mechanical, electrical and emission properties.

4.3.1 Grain structure and orientation

Tungsten filaments are usually fine equiaxed crystals with an average size of 1-5 microns. The drawing and annealing process forms a fibrous structure along the axial direction, with the grain orientation mainly in the <110> direction, accounting for 70-80%. The fibrous structure improves the tensile strength by strengthening the grain boundaries (increase by 15-20%), while optimizing the electronic conductive path and reducing the resistivity by 5%. Electron backscatter diffraction (EBSD) analysis shows that the <110> oriented grains have a lower creep rate at high temperatures and extend the filament life by 30%.

Grain size has a significant effect on performance. Too large grains (>10 microns) reduce mechanical strength and increase high temperature deformation; too small grains (<1 micron) increase grain boundary density and cause brittleness. The ideal size (2-4 microns) is controlled by doping and annealing, for example, potassium doping forms tiny bubbles, hindering grain boundary migration and maintaining uniform grains. SEM and transmission electron microscopy (TEM) observations show that the filament with optimized grain structure has a tensile strength of 400 MPa and an elongation at break of 8% at 2500°C.

4.3.2 Effect of doping elements on microstructure

Doping elements (such as potassium, aluminum, rhenium) optimize filament performance by changing grain growth and surface electronic structure:

Potassium (K, 0.01-0.05 wt %): forms bubbles with a diameter of 0.1-0.5 μm during sintering, which are distributed at the grain boundaries, hindering grain growth and maintaining the grain size of 2-3 μm. Potassium bubbles also increase grain boundary strength, reduce high temperature cracks, and extend service life by 20-40%.

Aluminum (Al, 0.005-0.02 wt %): promotes the exposure of the {100} crystal plane, reduces the work function by 0.2 eV, and increases the emission current density by 15%. The uniform distribution of aluminum atoms in the lattice (verified by TEM-EDS) optimizes electronic conductivity.

Rhenium (Re, 0.1-1 wt %): Improves lattice plasticity, reduces dislocation density, and increases ductility by 10%. Rhenium also inhibits high temperature recrystallization and maintains the fibrous structure.

The distribution of doping elements needs to be uniform to avoid local enrichment leading to uneven performance. Energy dispersive spectroscopy (EDS) analysis shows that tungsten doping reduces grain boundary defects by 30%, improves grain orientation consistency by 20%, and significantly enhances mechanical and emission properties.

4.3.3 Surface morphology and emission performance

Surface morphology, including roughness, crystal face exposure and microscopic defects, directly affects the uniformity and efficiency of thermal electron emission. The ideal surface roughness Ra < 0.05 microns is achieved by electrochemical polishing, which reduces local electric field concentration and improves emission consistency by 10%. Atomic force microscopy (AFM) analysis shows that the peak-to-valley height of the polished surface is < 10 nm, which is much lower than that of the untreated surface (50-100 nm).

Crystal face exposure is critical to emission performance. {100} facets are more favorable for electron escape than {110} facets (4.6 eV) due to their lower work function (4.3 eV). Doping with aluminum and surface coatings (such as yttrium oxide) increases the proportion of {100} facets by 20% and improves emission current density by 15%. Yttrium oxide coatings (thickness 0.1-1 micron) optimize surface electronic states by forming nanoscale crystal structures, further reducing the work function to 4.2 eV.

Surface defects (such as scratches and oxide residues) may cause local overheating or arc discharge, reducing emission efficiency. Chemical cleaning and plasma treatment remove defects, and the surface cleanliness reaches 99.9%, ensuring emission uniformity. Actual tests show that the emission current density deviation of the filament with optimized surface morphology at 2600°C is less than 1%, meeting the requirements of high-resolution electron guns.

4.4 Life and reliability of electron gun tungsten filaments

The life and reliability of electron gun tungsten filaments are key indicators that determine their application performance in high-precision equipment (such as scanning electron microscopes, X-ray tubes, and electron beam lithography equipment). The life of tungsten filaments is usually between 500-2000 hours and is affected by many factors, including working conditions, material properties, manufacturing processes, and environmental factors. This section discusses in detail the factors affecting filament life, the main failure modes and their analysis methods, and the standardized process of reliability testing to provide technical support for optimizing filament design and extending service life.

4.4.1 Factors affecting filament life

The life of tungsten filaments is affected by a combination of multiple internal and external factors. The following are the main factors and their mechanisms of action:

Working temperature

Function: Tungsten filaments usually work at 2500-2800°C. High temperature accelerates the evaporation of tungsten atoms, resulting in thinning of diameter and increased resistance.

Technical details: At 2700°C, the evaporation rate is about 0.01-0.05 mg/cm²·h, and the diameter thinning rate is 0.1-0.5 μm/h. For example, in a scanning electron microscope (SEM), after the filament diameter is thinned from 0.2 mm to 0.15 mm, the emission current density decreases by 20% and the lifetime is shortened to 500 hours. For every 100°C increase in temperature, the evaporation rate increases by about 4 times and the lifetime decreases by 50%.

Optimization strategy: Inhibit grain growth by doping with potassium (0.01-0.05 wt%) and reduce the evaporation rate by 30%. Surface coatings (such as zirconium oxide, thickness 0.5-1 micron) reduce the evaporation rate by 50% and extend the lifetime to 1500 hours.

Vacuum environment

Action: Residual gases (such as oxygen and nitrogen) trigger surface oxidation or arc discharge, accelerating filament degradation.

Technical details: Under 10^-5 Pa vacuum, oxygen partial pressure > 0.01 Pa will lead to the formation of tungsten trioxide (WO3, www.tungsten-oxide.com), increase the work function by 0.1-0.2 eV, and reduce the emission efficiency by 15%. Arc discharge (occurrence rate 0.01%) may cause filament breakage or electrode damage. For example, in X-ray tubes, when the vacuum degree is insufficient at 10^-7 Pa, the filament life is reduced from 2000 hours to 1000 hours.

Optimization strategy: Use a high vacuum system (10^-8 Pa) equipped with a turbomolecular pump (pumping speed 500-2000 L/s) to reduce the oxidation rate by 80%. High temperature baking (400°C, 24 hours) removes residual gas and extends the life by 25%.

Thermal cycle and thermal stress

Action: The hot and cold cycle of the electron gun (20-2700°C, heating rate 100°C/s) induces thermal stress, resulting in micro cracks at grain boundaries.

Technical details: After 1000 thermal cycles, the crack rate of pure tungsten filaments reached 5%, and the tensile strength decreased by 10% (from 800 MPa to 720 MPa). In transmission electron microscopy (TEM), thermal stress caused the beam to shift by 0.5 nm, affecting the resolution.

Doping with rhenium (0.1-1 wt%) improved ductility and reduced the crack rate to 1%.
Optimization strategy: Optimizing filament geometry (e.g., double helix, increasing the emission area by 30%) disperses thermal stress and reduces the crack rate by 20%. Slow heating (50°C/s) reduces stress accumulation and extends the life by 15%.

Current load
Effect: High emission current (e.g., 10-100 mA) increases the thermal load of the filament, accelerating evaporation and mechanical fatigue.
Technical details: In electron beam welding (EBW), a current of 100 mA causes a local increase in filament temperature by 50°C, increases the evaporation rate by a factor of 2, and reduces the life from 1000 hours to 600 hours. Current fluctuation >1% causes thermal non-uniformity, resulting in a 10% increase in breakage rate.
Optimization strategy: Using a constant current power supply (accuracy ±0.1 mA) to control current stability, the breakage rate is reduced by 50%. Multi-segment spiral filaments reduce local overheating through segmented emission and extend life by 20%.

Manufacturing defects
Effect: Surface defects (such as scratches, inclusions, Ra>0.05 microns) or internal pores cause local overheating and breakage.
Technical details: Surface scratches cause a 5% deviation in current density and a pattern deviation of >1 nm in EBL. Internal pores (diameter >1 micron) reduce tensile strength by 15% and the breakage rate reaches 2%. For example, the life of SEM filaments is reduced from 1500 hours to 800 hours due to surface oxide accumulation.
Optimization strategy: Electrochemical polishing (Ra<0.05 microns) eliminates surface defects and improves emission uniformity by 15%. X-ray tomography (resolution 0.1 microns) detects internal defects and reduces the scrap rate to 0.3%.

Doping and coating quality
Function: The non-uniformity of doping elements and coating affects thermal stability and emission efficiency.
Technical details: Potassium doping (0.01-0.05 wt%) with a deviation of >5% leads to uneven grain size (2-10 microns) and a 10% decrease in thermal stability. Yttria coating (thickness 0.1-1 micron) with a peeling rate of >1% will expose the tungsten substrate and increase the oxidation rate by 50%. In TEM, coating defects reduce the brightness by 20% (from 10^7 to 8×10^6 A/cm²·sr).
Optimization strategy: Powder metallurgy ensures doping uniformity (deviation <1%), chemical vapor deposition (CVD) controls coating thickness deviation <5%, and extends life by 30%.

4.4.2 Failure mode analysis (such as evaporation, fracture)

The failure modes of tungsten filaments mainly include evaporation, fracture, surface degradation and arc discharge, each of which has a significant impact on life and performance. The following is a detailed analysis:

Evaporation

Definition: Tungsten atoms escape from the surface at high temperatures, resulting in thinning of the filament diameter and performance degradation.

Mechanism: At 2700°C, the evaporation rate is 0.01-0.05 mg/cm²·h, the diameter is thinned by 0.1-0.5 μm/h, the resistance increases by 20%, and the emission current density decreases by 30%. For example, in SEM, after the filament evaporates to a diameter of <0.15 mm, the brightness drops from 10^6 to 5×10^5 A/cm²·sr, and the imaging quality decreases.

Influencing factors: working temperature (>2600°C), vacuum (>10^-7 Pa), surface roughness (Ra>0.05 microns).

Analysis method: Observe the diameter change by scanning electron microscopy (SEM) (accuracy ±0.1 microns), and measure the evaporation rate by thermogravimetric analysis (TGA, accuracy ±0.01 mg).

Optimization measures: Aluminum doping (0.005-0.02 wt%) reduces the evaporation rate by 30%, and zirconium oxide coating (thickness 0.5 micron) reduces the evaporation rate by 50%. Intelligent monitoring system (infrared temperature measurement, accuracy ±2°C) adjusts the temperature in real time and extends the life by 20%.

Fracture

Definition: Brittle or ductile fracture of the filament caused by thermal stress or mechanical fatigue.

Mechanism: Thermal cycling (20-2700°C, 1000 times) induces microcracks (length 1-10 microns) at grain boundaries, and the tensile strength decreases by 15%. High current (>10 mA) causes local overheating and increases the fracture rate by 10%. For example, in EBW, filament breakage leads to welding interruption and downtime >4 hours.

Influencing factors: Grain size (>5 microns), thermal stress (>100 MPa), surface defects (scratch depth >1 micron).

Analysis methods: Fracture analysis (SEM, magnification 1000 times) to determine the cause of cracks (grain boundary or surface), electron backscatter diffraction (EBSD) to analyze grain orientation (<110> accounts for 80%).

Optimization measures: Rhenium doping (0.1-1 wt%) improves ductility by 20%, double helix design disperses stress, and fracture rate is reduced by 30%. Slow heating (50°C/s) reduces thermal shock and extends life by 15%.

Surface degradation

Definition: Surface performance degradation caused by oxidation, contaminant accumulation or coating peeling.

Mechanism: At 10^-5 Pa, oxygen triggers WO3 formation (thickness 0.1-1 micron), work function increases by 0.2 eV, and emission efficiency decreases by 15%. Coating peeling (>1%) exposes the tungsten substrate and increases oxidation rate by 50%. For example, in X-ray tubes, surface degradation reduces imaging resolution to 0.8 mm.

Influencing factors: vacuum degree (>10^-7 Pa), coating quality (uniformity deviation>5%), residual gas (O2>0.01 Pa).

Analysis method: X-ray photoelectron spectroscopy (XPS, accuracy ±0.1 at%) analyzes surface

chemical composition, and atomic force microscopy (AFM, accuracy ±1 nm) measures roughness (Ra<0.05 microns).
Optimization measures: High vacuum (10^-8 Pa) reduces oxidation rate by 80%, and atomic layer deposition (ALD) coating (thickness 10-50 nm) improves adhesion and reduces peeling rate to 0.5%.

Arc discharge
Definition: Abnormal discharge caused by residual gas or surface defects, resulting in filament damage or breakage.
Mechanism: At 10^-6 Pa, the arc occurrence rate is 0.01%, and the local temperature rises>3000°C, causing melting or fracture. For example, in TEM, arcing causes the beam to shift by 1 nm and the resolution drops to 0.3 nm.
Influencing factors: vacuum degree (>10^-7 Pa), surface roughness (Ra>0.05 microns), electrode spacing (deviation>0.01 mm).
Analysis method: high-frequency oscilloscope (sampling rate 1 GHz) records arc waveform, mass spectrometer (accuracy ±0.01 ppm) analyzes residual gas.
Optimization measures: precision electrode design (spacing tolerance ±0.01 mm) reduces arc risk by 50%, high temperature baking (400°C, 24 hours) removes gas, and the incidence rate drops to 0 ascended

Optimization measures: precision electrode design (spacing tolerance ±0.01 mm) reduces arc risk by 50%, high temperature baking (400°C, 24 hours) removes gas, and the incidence rate drops to 0.001%.

4.4.3 Reliability test method
Reliability test evaluates the life, performance stability and failure risk of tungsten filaments through standardized methods to ensure its reliability in practical applications. The following are the main test methods:

Accelerated life test
Definition: simulate long-term operation under high temperature and high current conditions to predict filament life.
Method: Run in a 2700°C, 10^-7 Pa vacuum chamber for 1000 hours, with an emission current of 10-100 mA and recording the current density decay (target <5%). Measure the diameter (SEM, accuracy ±0.1 micron) and resistance (four-probe method, ±0.1 μΩ·cm) every 100 hours.
Application scenario: In SEM filament testing, the accelerated life test predicts a life of 1500 hours and an evaporation rate of 0.02 mg/cm²·h, which meets the GB/T 15065 standard.
Technical details: Use a picoammeter (accuracy ±0.1 μA) to measure current and an infrared thermometer (±5°C) to monitor temperature. Fit the data to the Weibull distribution and predict the failure time (error <5%).
Optimization: The automated test platform (response time <1 s) improves efficiency by 50% and batch consistency >99%.

Thermal Cycle Test

Definition: Simulate thermal and cold cycles (20-2700°C, 1000 times) to evaluate thermal stress and mechanical stability.

Method: Heating rate 100°C/s, cooling to 20°C, cycle time 10 minutes. Detect cracks (SEM, magnification 1000 times) and tensile strength (universal testing machine, ±0.1 MPa).

Application scenario: In TEM filament testing, thermal cycle testing shows that the crack rate of rhenium-doped filaments is <1%, and the tensile strength remains at 400 MPa.

Technical details: EBSD is used to analyze grain orientation (<110> accounts for 80%), and fracture analysis determines the cause of cracks (grain boundary or surface). The test complies with ISO 11539 standard.

Optimization: Slow heating (50°C/s) reduces the crack rate by 20%, and the automatic recording system (accuracy ±0.1%) improves data reliability.

Emission stability test

Definition: Measures current fluctuations and brightness decay during long-term operation.

Method: Run at 2600°C, 10^-8 Pa for 500 hours, emission current 1-10 μA, record fluctuations (target <0.5%). Use picoammeter (±0.01 μA) and brightness meter (10^5-10^8 A/cm²·sr).

Application scenario: In EBL filament testing, stability testing shows current fluctuation of 0.1% and brightness decay of <3%, meeting the requirements of 7 nm node chip manufacturing.

Technical details: The current is adjusted by a feedback control system (response time <1 ms), and the data conforms to the normal distribution (σ<1%). The test follows the DIN EN 60695 standard.

Optimization: AI algorithm (accuracy >95%) predicts fluctuation trends, adjusts power supply parameters, and improves stability by 10%.

Antioxidation test

Definition: Evaluate the surface stability of the filament in a trace oxygen environment.

Method: Measure oxide layer thickness (XPS, ±0.1 nm) at 10^-5 Pa, 2600°C for 1000 hours with an oxygen partial pressure of 0.01 Pa.

Application scenario: Yttria-coated filament oxide layer thickness <0.1 micron and work function change <0.1 eV in X-ray tube filament testing.

Technical details: SEM observation of oxide morphology (WO3 grains <100 nm), TGA measurement of mass loss (±0.01 mg). Tests comply with ISO 6848.

Optimization: High vacuum (10^-8 Pa) reduces oxidation rate by 80%, ALD coating (thickness 10 nm) improves oxidation resistance by 50%.

Failure mode analysis

Definition: Identify failure causes and propose improvement measures through multiple technical means.

Method: Combine SEM (fracture analysis), XPS (surface chemistry), EBSD (grain structure) and TGA (evaporation rate) to analyze evaporation, fracture, surface degradation and arc discharge.

Application scenario: In the EBW filament test, analysis shows that 80% of failures are caused by surface oxidation, and the life is extended by 40% after improving the coating process.

Technical details: Data is integrated into the FMECA (Failure Mode, Effects and Hazard Analysis) model, and the risk priority (RPN) is <100. The analysis report meets ISO 9001 requirements.
Optimization: Machine learning (accuracy>95%) predicts failure modes, optimizes doping (rhenium 0.1 wt%) and coating (zirconia 0.5 microns), and the scrap rate is reduced to 0.2%.

Reliability testing ensures the stability of filaments in actual applications. Test data must be recorded for 5 years in accordance with ISO 9001 and GB/T 9383 standards. In the future, it is necessary to develop a multi-parameter integrated test platform (cost reduced to 50% of the current level) and improve efficiency by 30%.

4.5 MSDS of Electron Gun Tungsten Filament from CTIA GROUP LTD

The Material Safety Data Sheet (MSDS) provides standardized information on the safe use, storage and disposal of electron gun tungsten filaments, in compliance with GB/T 16483 and OSHA requirements. The following are details to ensure safety compliance during production, transportation and use.

Part I: Product Name
English Name: Electron Beam Tungsten Filament
CAS No.: 7440-33-7

Part II: Ingredients/Composition Information
Content W≥99.95%
Total impurity content ≤0.05%

Part III: Hazard Overview
Health Hazard: This product is non-irritating to eyes and skin.
Explosion Hazard: This product is non-flammable and non-irritating.

Part IV: First Aid Measures
Skin Contact: Take off contaminated clothing and rinse with plenty of running water.
Eye Contact: Lift eyelids and rinse with running water or saline. Seek medical attention.
Inhalation: Leave the scene to fresh air. If breathing is difficult, give oxygen. Seek medical attention.
Ingestion: Drink plenty of warm water and induce vomiting. Seek medical attention.

Part V: Firefighting Measures
Harmful combustion products: Natural decomposition products are unknown.
Fire Extinguishing Method: Firefighters must wear gas masks and full-body fire suits and extinguish fires in the upwind direction. Fire Extinguishing Agent: Dry leather powder, sand and soil.

Part VI: Leakage Emergency Treatment
Emergency Treatment: Isolate the leaked contaminated area and restrict entry and exit. Cut off the source of fire. It is recommended that emergency response personnel wear dust masks (full-face

masks) and anti-toxic clothing. Avoid raising dust, sweep it carefully, place it in a bag and transfer it to a safe place. If there is a large amount of leakage, cover it with plastic sheeting or canvas. Collect and recycle it or transport it to a waste treatment site for disposal.

Part VII: Operation, disposal and storage

Operation precautions: Operators must undergo special training and strictly abide by the operating procedures. It is recommended that operators wear self-priming filter dust masks, chemical safety protective glasses, anti-toxic penetration work clothes, and rubber gloves. Stay away from fire and heat sources, and smoking is strictly prohibited in the workplace. Use explosion-proof ventilation systems and equipment. Avoid generating dust. Avoid contact with oxidants and halogens. Load and unload gently during transportation to prevent damage to packaging and containers. Equip with corresponding types and quantities of fire-fighting equipment and leakage emergency treatment equipment. Empty containers may have residual harmful substances.

Storage precautions: Store in a cool and ventilated warehouse. Keep away from fire and heat sources. It should be stored separately from oxidants and halogens, and must not be mixed. Equip with corresponding types and quantities of fire-fighting equipment. The storage area should be equipped with appropriate materials to contain leaks.

Part VIII: Contact Control/Personal Protection

China MAC (mg/m3): 6

Former Soviet Union MAC (mg/m3): 6

TLVTN: ACGIH 1mg/m3

TLVWN: ACGIH 3mg/m3

Monitoring method: Potassium thiocyanate-titanium chloride spectrophotometry

Engineering control: The production process is dust-free and fully ventilated.

Respiratory system protection: When the dust concentration in the air exceeds the standard, a self-priming filter dust mask must be worn. When rescuing and evacuating in an emergency, an air respirator should be worn.

Eye protection: Wear chemical safety glasses.

Body protection: Wear work clothes that prevent toxic penetration.

Hand protection: Wear rubber gloves.

Part IX: Physical and Chemical Properties

Main Ingredients: Pure

Appearance and Properties: Solid, metallic bright white

Melting Point (°C): N/A

Boiling Point (°C): N/A

Relative Density (Water = 1): 13~18.5 (20°C)

Vapor Density (Air = 1): No Data

Saturated Vapor Pressure (kPa): No Data

Heat of Combustion (kj/mol): No Data

Critical Temperature (°C): No Data

Critical Pressure (MPa): No Data
Logarithm of Water Partition Coefficient: No Data
Flash Point (℃): No Data
Ignition Temperature (℃): No Data
Upper Explosion Limit % (V/V): No Data
Lower Explosion Limit % (V/V): No Data
Solubility: Soluble in nitric acid and hydrofluoric acid

Part X: Stability and Reactivity
Prohibited Incompatibility: Strong Acids and Bases

Part XI:
Acute toxicity: No data
LC50: No data

Part XII: Ecological information
No data for this part

Part XIII: Waste disposal
Waste propertiesWaste disposal methods: Refer to relevant national and local regulations before disposal. Recycle if possible.

Part XIV: Transportation information
Packaging category: Z01
Transportation precautions: The packaging should be complete and the loading should be secure at the time of shipment. During transportation, ensure that the container does not leak, collapse, fall or damage. It is strictly forbidden to mix and transport with oxidants, halogens, edible chemicals, etc. During transportation, it should be protected from exposure to sunlight, rain and high temperature. The vehicle should be thoroughly cleaned after transportation.

Part XV: Supplier information
Supplier: CTIA GROUP LTD
Tel: 0592-5129696/5129595

CTIA GROUP LTD Electron Beam Tungsten Filament

Chapter 5: Purpose and Application of Tungsten Filament in Electron Gun

Tungsten filaments in electron guns are widely used in scientific research, industrial manufacturing, medical equipment, and emerging technologies. Their high melting point, low vapor pressure, and high emission efficiency make them the core components of electron guns, driving a variety of applications from nanoscale imaging to high-precision processing. This chapter discusses in detail the specific uses of tungsten filaments in electron guns, vacuum electronic devices, industrial and scientific research applications, and emerging fields, and analyzes their performance requirements, technical challenges, and optimization directions.

5.1 Application in electron gun

Electron guns use tungsten filaments to generate high-energy electron beams and are widely used in microscopes, processing equipment, and semiconductor manufacturing. This section explores the key role of tungsten filaments in scanning electron microscopy (SEM), transmission electron microscopy (TEM), electron beam welding and cutting, and electron beam lithography.

5.1.1 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) uses an electron beam generated by a tungsten filament to scan the surface of a sample, and forms a high-resolution image by detecting secondary electrons, backscattered electrons or characteristic X-rays. It is widely used in materials science, biology and semiconductor analysis. The resolution of SEM is usually 1-5 nm, and the depth of field is large, which is suitable for observing complex three-dimensional structures.

Tungsten filament in SEM is to provide high brightness and stable electron beam. Typical working conditions include:

Emission current: 1-10 μA, fluctuation must be kept less than 1% to ensure imaging stability.

Brightness: 10^5-10^6 A/cm²· sr , affects resolution and signal strength.

Working temperature: 2500-2700°C, balancing emission efficiency and lifespan.

Vacuum degree: 10^-7 Pa, to prevent oxidation and arc discharge.

Tungsten filaments directly affects the resolution and imaging quality of SEM. For example, in high-resolution mode, the filament needs to provide an electron beam with a narrow beam width (<5 nm), and potassium doping (0.01-0.05 wt %) can improve emission uniformity by 15% by optimizing the grain structure. Surface coatings (such as yttrium oxide, 0.1-1 micron thickness) reduce the work function (from 4.5 eV to 4.2 eV) and increase the brightness by 20%, which is suitable for observing nanoscale features, such as defects in semiconductor wafers or ultrastructures of biological samples.

Filament life is a key factor in SEM operating costs. Standard tungsten filament life is 500-2000 hours, and can be extended to 3000 hours by optimizing doping and coating. For example, double helix filaments increase the emission area to reduce local overheating and increase life by 30%. In practical applications, the filament replacement cycle affects equipment downtime, and the automated filament alignment system (accuracy ±1 micron) can reduce maintenance time by 50%. Technical challenges include:

Emission stability: Current fluctuations (>1%) cause image noise, requiring a constant current power supply (accuracy ±0.1 mA) and a high vacuum environment.

Lifespan and cost: Frequent replacement of filaments increases operating costs, and long-life filaments need to be developed (target 5,000 hours).

Miniaturization: Portable SEM requires the filament diameter to be reduced to 0.05-0.1 mm while maintaining high brightness.

Optimization strategies include the use of nano-scale surface treatment (such as plasma polishing, Ra < 0.02 microns) and intelligent monitoring systems (real-time detection of current and temperature) to reduce the scrap rate to less than 0.5% and improve imaging quality by 10%.

5.1.2 Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) uses high-energy electron beams to penetrate thin samples and generate atomic-level resolution images (0.1-0.2 nm). It is widely used in crystal structure analysis, nanomaterial characterization, and biomolecular imaging. TEM has higher performance requirements for tungsten filaments than SEM, requiring higher brightness and narrower beam width.

Tungsten filament in TEM include:

Emission current: 10-50 μA, with fluctuation less than 0.5% required to ensure atomic-level resolution.

Brightness: 10^7-10^8 A/cm²· sr , high emission efficiency is required to support high-resolution imaging.

Working temperature: 2600-2800°C, high thermal stability is required to maintain long-term operation.

Vacuum degree: 10^-8 Pa, to prevent electron beam scattering and filament oxidation.
tungsten filaments is the key to TEM resolution. For example, in high-resolution TEM (HRTEM), the filament needs to provide an electron beam with a beam width of <0.5 nm. Doping with aluminum (0.005-0.02 wt %) and yttrium oxide coating increases the brightness by 30% and reduces the work function to 4.2 eV, meeting the requirements of sub-angstrom imaging. Double helix or tapered filaments improve beam focusing by optimizing the electric field distribution, and reduce beam width deviation by 20%.

Filament life is particularly important for TEMs due to the high cost of replacement (including vacuum system maintenance). Optimized filaments have a life of 800-1500 hours at 2600°C, and rhenium- doped (0.1-1 wt %) filaments can reach 2000 hours, reducing mechanical fracture by increasing ductility. Surface polishing (Ra < 0.05 microns) and high vacuum environment (10^-8 Pa) reduce evaporation rate by 50% and extend life by 25%.

Technical challenges include:

High brightness requirement: TEM requires 10^8 A/cm²· sr brightness, which is difficult to meet with pure tungsten filaments. New coatings or composite materials are needed.

Thermal drift: Filament temperature fluctuations (>5°C) cause beam drift and require precise temperature control (±2°C).

Long life: High operating temperature accelerates evaporation, and high temperature resistant coatings (such as zirconium oxide) need to be developed.

Optimization strategies include using nanostructured tungsten filaments (grain size <100 nm) to improve emission efficiency by 20%, and integrating an AI monitoring system to predict filament life and reduce unexpected failures by 50%.

CTIA GROUP LTD

Electron Beam Tungsten Filaments Introduction

1. Overview of Electron Beam Tungsten Filaments

The electronic beam tungsten filament is a high-performance thermionic cathode component specifically designed for electron beam (EB) equipment. Made from high-purity tungsten material, it features an ultra-high melting point, excellent thermionic emission capability, and long service life, allowing stable operation in high-vacuum environments. It is widely used in fields such as electron beam welding, electron beam evaporation coating, scanning electron microscopy (SEM), and X-ray tubes.

2. Features of Electron Beam Tungsten Filaments

Ultra-High Heat Resistance: Stable operation under high-temperature and high-vacuum conditions for extended periods.

Excellent Thermionic Emission Performance: Provides efficient electron emission under low power consumption

High-Purity Material: W ≥ 99.95% reduces contamination during electron emission and ensuring stable device operation.

Long Service Life: Resistant to creep, evaporation, and high-temperature oxidation.

Precision Manufacturing: Strict dimensional accuracy control ensures a stable electron beam.

Multiple Structure Options: Tailored to different electronic gun equipment requirements.

3. Some Types of Electron Beam Tungsten Filaments

Mosquito Coil	Pull-type	U-shaped
		
Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm
U-shaped with Folding Tails	**Half Moon**	**Hook type**
		
Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm

4. Purchasing Information

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

Website: www.tungsten.com.cn

5.1.3 Electron beam welding and cutting

Electron beam welding (EBBW) and cutting uses a high-energy electron beam (10-100 kW) generated by a tungsten filament to melt or vaporize materials for high-precision processing. It is widely used in aerospace, automotive manufacturing and nuclear industries. EBW can form deep welds (depth-to-width ratio >20:1) and has a cutting accuracy of ±0.01 mm.

Tungsten filament in EBW and cutting include:

Emission current: 10-100 mA, high current supports high power output.

Accelerating voltage: 50-150 kV, generating high energy electron beam.

Working temperature: 2600-2800°C, must withstand high heat loads.

Vacuum degree: 10^-5 Pa, slight residual gas is allowed.

The filament needs to provide a high-power, stable electron beam. For example, in EBW , the filament generates a 60 kW electron beam, and when welding titanium alloy (50 mm thickness), the weld width is <1 mm and the heat-affected zone is <0.5 mm. Potassium-doped filaments improve thermal stability by inhibiting grain growth and have a lifespan of 1000 hours. Surface coatings (such as zirconium oxide) reduce the work function and increase the emission current density by 20%, supporting high power output.

In cutting applications, the filament needs to provide an electron beam with a narrow beam width (<0.1 mm). When cutting stainless steel (thickness 10 mm), the cut smoothness Ra is <0.1 micron. The double helix filament increases the emission area to improve beam stability, and the current fluctuation is <1%. The high vacuum environment (10^-5 Pa) reduces beam scattering and ensures processing accuracy.

Technical challenges include:

High power stability: Current fluctuations (>2%) lead to uneven welds, requiring a constant current power supply (accuracy ±0.5 mA).

Filament life: High current accelerates evaporation, requiring a long-life filament (target 2000 hours).

Residual gas: Oxygen at 10^-5 Pa may cause oxidation and require surface protective coating.

Optimization strategies include using composite tungsten filaments (such as tungsten-yttrium oxide) to increase emission efficiency by 30%, and a real-time beam current monitoring system (accuracy ±0.1 μA) to ensure processing consistency.

5.1.4 Electron beam lithography

Electron beam lithography (EBL) uses an electron beam generated by a tungsten filament to directly write nanoscale patterns to manufacture semiconductor devices, masks and nanostructures. The resolution can reach <10 nm and it is widely used in chip research and development and quantum device manufacturing.

The tungsten filament in the EBL include:

Emission current: 1-10 nA, extremely high stability required (fluctuation <0.1%).

Brightness: 10^7-10^8 A/cm²· sr, supports nanoscale focusing.

Operating temperature: 2500-2700°C, balanced emission and lifespan.

Vacuum degree: 10^-8 Pa, to prevent beam scattering.

The emission consistency of the filament is the key to EBL. For example, when manufacturing 7 nm node chips, the filament needs to provide an electron beam with a beam width of <5 nm. Doping with aluminum and yttrium oxide coatings will increase the brightness by 25%, ensuring pattern accuracy of ±1 nm. The double-helix filament improves beam stability by optimizing the electric field distribution, and the current deviation is <0.05%. The filament life needs to be more than 500 hours. Due to the high maintenance cost of EBL equipment, rhenium- doped filaments can reach 1,000 hours, and the evaporation rate is reduced by 40%.

Technical challenges include:

Ultra-high stability: Current fluctuations (>0.1%) cause pattern distortion, requiring an ultra-precise power supply (accuracy ±0.01 nA).

Long life: The demand for high brightness accelerates filament loss and requires new materials (such as nanostructured tungsten).

Beam focusing: Nanoscale patterns require sub-nanometer beam widths, which require optimized filament geometry and electrode design.

Optimization strategies include the use of field- assisted emission coatings (such as thoria) to increase brightness by 30%, and an integrated beam feedback system (response time <1 ms) to ensure real-time calibration.

5.2 Vacuum Electronic Devices

Vacuum electron devices use tungsten filaments to generate electron currents, driving microwave, X-ray and display technologies. This section discusses their applications in microwave tubes, X-ray tubes and cathode ray tubes.

5.2.1 Microwave tubes (such as magnetrons and traveling wave tubes)

Microwave tubes use tungsten filaments to generate electron flow, which generates high-frequency electromagnetic waves under the action of magnetic or electric fields. They are widely used in radar, satellite communications and microwave heating. Magnetrons are used in microwave ovens and military radars, and traveling wave tubes (TWTs) are used in high-frequency communications.

Tungsten filament in the microwave tube include:

Emission current: 1-10 mA, stability <1% required to ensure signal quality.

Operating temperature: 2400-2600°C, balanced emission and lifespan.

Vacuum degree: 10^-6 Pa, to prevent arcing and oxidation.

Power output: Magnetron 1-10 kW, TWT 10-100 W.

In a magnetron, the filament provides 5 mA of electron current, generating 2.45 GHz microwaves with a power of 1 kW. Potassium-doped filaments extend their life to 5,000 hours by improving thermal stability, making them suitable for household microwave ovens. Traveling wave tubes require higher stability, with filament current fluctuations of <0.5%. Doping with aluminum and yttrium oxide coatings increases emission efficiency by 20%, supporting 10 GHz high-frequency signals.

Technical challenges include:

High stability: Current fluctuations (>1%) cause signal distortion and require a precision power supply (accuracy ±0.1 mA).

Long life: High power output accelerates evaporation and requires a high temperature resistant coating.

Miniaturization: Satellite TWT requires filament diameter < 0.1 mm to maintain high emission.

Optimization strategies include using nanoscale grain filaments (grains <100 nm) to increase emission efficiency by 15%, and vacuum packaging technology (10^-7 Pa) to extend lifetime by 30%.

5.2.2 X-ray tube

X-ray tubes use tungsten filaments to generate electron beams, which bombard metal targets (such as tungsten or molybdenum) to produce X-rays. They are widely used in medical imaging (CT, X-ray machines) and industrial non-destructive testing.

Tungsten filament in X-ray tube include:

Emission current: 1-10 mA, supports high-intensity X-rays.
Accelerating voltage: 30-150 kV, determines the X-ray energy.

Working temperature: 2500-2700°C, high thermal stability required .

Vacuum degree: 10^-7 Pa, to prevent oxidation and arcing.

The filament needs to provide high emission efficiency and long life. For example, in CT scanning, the filament generates 5 mA electron current, produces 120 kV X-rays, and has an imaging resolution of <0.5 mm. Potassium-doped filaments have a lifespan of 1000-3000 hours, and surface coatings (such as zirconium oxide) increase the emission current density by 20%, supporting high-throughput imaging. Double-helix filaments reduce local overheating by increasing the emission area and extend the life by 25%.

Technical challenges include:

High intensity requirements: High-dose X-rays require high current (>10 mA), which accelerates filament loss.

Thermal management: The distance between the filament and the target is small (<10 mm), and efficient heat dissipation is required.

Lifetime cost: Frequent filament replacement increases medical equipment maintenance costs.

The optimization strategies include using a composite tungsten filament (e.g., tungsten-yttrium oxide) to increase the emission efficiency by 30%, and an integrated cooling system (water cooling, flow rate 0.5 L/min) to reduce the filament temperature by 50°C.

5.2.3 Cathode Ray Tube (CRT)

Cathode ray tubes (CRTs) use tungsten filaments to generate electron beams that bombard a fluorescent screen to produce images. They are used in traditional displays, industrial monitoring, and aviation instruments. Although LCDs and OLEDs are gradually replacing CRTs, they are still used in specific areas (such as high-reliability displays).

Tungsten filament in CRT include:

Emission current: 0.1-1 mA, low current supports display function.

Working temperature: 2000-2200°C, low temperature prolongs service life.

Vacuum degree: 10^-6 Pa, to prevent contamination of the fluorescent screen.

Accelerating voltage: 10-30 kV, produces bright images.

The filament needs to provide a stable, low-power electron flow. For example, in aviation displays, the filament generates 0.5 mA electron flow, produces high-contrast images, and has a lifespan of 5,000-10,000 hours. Potassium-doped filaments increase emission efficiency by 15% by reducing the work function. Single-helix filaments have a simple structure and low cost, making them suitable for large-scale production.

Technical challenges include:
Long life: CRT needs to have an ultra-long life (>10,000 hours), and high-temperature evaporation is the bottleneck.

Low power consumption: The display requires low heating power (<50 W) and optimized filament geometry.

Environmental adaptability: Aviation CRTs need to withstand vibration (10-100 Hz) and temperature changes (-40 to 70°C).

Optimization strategies include using low-work-function coatings (such as thorium oxide) to reduce operating temperature by 100°C, and anti-vibration design (filament fixing accuracy of ±1 micron) to improve reliability by 20%.

5.3 Other industrial and scientific research applications

Tungsten filaments have important applications in thin film deposition, ion sources, mass spectrometers and nuclear fusion experimental devices, supporting industrial production and cutting-edge scientific research.

5.3.1 Thin film deposition (such as physical vapor deposition)

Physical vapor deposition (PVD) uses a tungsten filament to generate an electron beam to evaporate or sputter materials to deposit thin films (0.1-10 microns thick) for applications in optical coatings, semiconductor manufacturing, and wear-resistant coatings.

Tungsten filament in PVD include:

Emission current: 1-10 mA, supports material evaporation.

Working temperature: 2500-2700°C, high thermal stability required .

Vacuum degree: 10^-6 Pa, to prevent film contamination.

Power output: 1-10 kW, driving the evaporation source.

The filament needs to provide a stable high-energy electron beam. For example, in optical coatings, the filament generates a 5 mA electron current, evaporates silicon dioxide (SiO_2), and deposits an anti-reflection film with a thickness of 0.5 microns and a uniformity of ±1%. Aluminum-doped filaments increase emission efficiency by 20%, and double-helix filaments reduce current fluctuations to <1%, ensuring film quality.

Technical challenges include:

Thin film uniformity: Uneven beam current leads to thickness deviation, and filament geometry needs to be optimized.

Long life: High power accelerates evaporation and requires high temperature resistant coating.

Material compatibility: Different evaporation materials require adjustment of beam parameters.

The optimization strategy includes using a multi-segment spiral filament to improve beam uniformity by 15%, and a real-time beam control system (accuracy ±0.1 μA) to ensure deposition consistency.

5.3.2 Ion source and mass spectrometer

The ion source uses a tungsten filament to generate an electron flow, ionizing gas molecules to form an ion beam, which is used in mass spectrometry, ion implantation and surface analysis. Mass spectrometers are used for chemical analysis with a resolution of 10^-6 Da.

Tungsten filament in the ion source include:

Emission current: 0.1-1 mA, high stability required (fluctuation <0.1%).

Operating temperature: 2400-2600°C, balanced emission and lifespan.

Vacuum degree: 10^-7 Pa, to prevent ion beam scattering.

Ionization efficiency: >10%, supporting high sensitivity analysis.

The filament needs to provide a stable low-power electron flow. For example, in a mass spectrometer, the filament generates a 0.5 mA electron flow, ionizing helium and producing a 10^6 cps ion signal. The potassium-doped filament has a lifespan of 2000 hours, and the surface polishing (Ra < 0.05 microns) reduces current fluctuations by 50%, improving analytical accuracy.

Technical challenges include:

Ultra-high stability: Current fluctuations (>0.1%) reduce resolution and require a precision power supply.

Long life: Frequent replacement of filaments affects analysis efficiency.

Miniaturization: Portable mass spectrometers require small filaments (diameter < 0.1 mm).

Optimization strategies include the use of field emission assist coatings to increase emission efficiency by 20%, and an integrated current feedback system (response time <1 ms) to ensure stability.

5.3.3 Nuclear fusion experimental device

Nuclear fusion experimental devices (such as tokamaks and inertial confinement fusion) use tungsten filaments to generate high-energy electron flow, drive plasma or diagnostic systems, and study the behavior of high-temperature plasma.

Tungsten filament in nuclear fusion device include:

Emission current: 10-100 mA, supports high power plasma.

Working temperature: 2700-3000°C, extremely high thermal stability required.

Vacuum degree: 10^-8 Pa, to prevent contamination.

Radiation resistance: Resistant to neutrons and gamma rays.

The filament needs to withstand extreme conditions. For example, in a tokamak, the filament generates 50 mA of electron current, drives a 1 keV plasma, and operates for 1000 hours. Rhenium-doped filaments withstand thermal shock by increasing ductility, and zirconium oxide coatings reduce the evaporation rate by 50%, allowing high-temperature operation.

Technical challenges include:

Extreme environments: High temperatures (>3000°C) and radiation accelerate filament degradation.

High power: High current (>100 mA) requires high transmission efficiency.

Long life: The device has high maintenance costs and requires ultra-long life filaments (>5000 hours).

Optimization strategies include using tungsten-based composite materials (such as tungsten-tungsten carbide) to improve radiation resistance by 30%, and vacuum sealing technology (10^-9 Pa) to extend life by 40%.

5.4 Emerging Application Areas

Tungsten filaments have shown great potential in emerging fields such as 3D printing, space propulsion and nanotechnology, driving technological innovation.

5.4.1 Electron Beam Melting in 3D Printing

Electron beam melting (EBM) uses a tungsten filament to generate a high-energy electron beam (50-100 kW) to melt metal powders and manufacture complex parts with an accuracy of ±0.1 mm. It is widely used in aerospace and medical implants.

Tungsten filament in EBM include:

Emission current: 10-50 mA, supports high power melting.

Accelerating voltage: 60-100 kV, generating high energy beam.

Working temperature: 2600-2800°C, high thermal stability required .

Vacuum degree: 10^-5 Pa, slight dust is allowed.

The filament needs to provide a high-power, stable electron beam. For example, when manufacturing titanium alloy aviation parts, the filament generates a 30 mA electron flow, melts the powder to form a layer thickness of 0.05 mm, and the surface roughness Ra<5 microns. The life of the potassium-doped filament is up to 1000 hours, and the double-helix filament improves the beam stability by 20%.

Technical challenges include:

High power stability: Current fluctuations (>2%) result in uneven layer thickness.

Dust pollution: Metal powder may contaminate the filament and require protective coating.

Long life: High power accelerates evaporation and requires high temperature resistant materials.

The optimization strategy includes the use of thorium oxide coating to increase the emission efficiency by 30%, and a beam scanning system (accuracy ±0.1 mm) to ensure melting uniformity.

5.4.2 Electron Sources in Space Propulsion Systems

Tungsten filaments are used as electron sources in ion thrusters and Hall effect thrusters to ionize propellants (such as xenon) to generate thrust, which are used in satellites and deep space exploration.

Tungsten filaments in space propulsion include:

Emission current: 1-10 mA, supports efficient ionization.

Working temperature: 2500-2700°C, long life required.

Vacuum degree: 10^-8 Pa, able to withstand space vacuum.

Radiation resistance: Resistant to cosmic rays and solar wind.

The filament needs to provide a steady flow of electrons. For example, in an ion thruster, the filament generates 5 mA of electrons, ionizing xenon gas to produce 0.1 N of thrust, and has a lifetime of several years. Rhenium- doped filaments withstand vibrations (10-100 Hz) by increasing ductility, and yttrium oxide coatings extend lifetime by 50%.

Technical challenges include:

Ultra-long life: Space missions require a lifespan of >10,000 hours.

Environmental adaptability: Need to withstand -100 to 100°C and radiation.

Low power consumption: The thrusters require low heating power (<100 W).

Optimization strategies include using field emission-assisted filaments to reduce operating temperature by 100°C, and radiation-resistant coatings such as zirconium oxide to improve reliability by 30%.

5.4.3 Nanotechnology and micro-nano processing

Tungsten filaments generate electron beams in electron beam induced deposition (EBID) and nanolithography to fabricate nanoscale structures for applications in sensors, quantum devices, and MEMS with a resolution of 1-5 nm.

Tungsten filament in micro-nano processing include:

Emission current: 0.1-1 nA , ultra-high stability required (fluctuation <0.05%).

Brightness: 10^8 A/cm²· sr , supports nanoscale focusing.

Working temperature: 2500-2700°C, long life required.

Vacuum degree: 10^-8 Pa, to prevent beam scattering.

The filament needs to provide an electron beam with an extremely narrow beam width . For example, in EBID, the filament generates a 0.5 nA electron current and deposits carbon nanowires (diameter <5 nm) with an accuracy of ±0.5 nm. Doping the filament with aluminum and thorium oxide coating increases the brightness by 30% and the lifetime by 500 hours.

Technical challenges include:

Ultra-high resolution: <1 nm beam width is required and filament geometry needs to be optimized.

Stability: Current fluctuations (>0.05%) lead to structural defects.

Miniaturization: Nanofabrication equipment requires small filaments (diameter < 0.05 mm).

The optimization strategy includes the use of nanostructured tungsten filaments to increase emission efficiency by 20%, and a beam calibration system (accuracy ±0.01 nA) to ensure processing accuracy.

CTIA GROUP LTD Electron Beam Tungsten Filament

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Electron Beam Tungsten Filaments Introduction

1. Overview of Electron Beam Tungsten Filaments

The electronic beam tungsten filament is a high-performance thermionic cathode component specifically designed for electron beam (EB) equipment. Made from high-purity tungsten material, it features an ultra-high melting point, excellent thermionic emission capability, and long service life, allowing stable operation in high-vacuum environments. It is widely used in fields such as electron beam welding, electron beam evaporation coating, scanning electron microscopy (SEM), and X-ray tubes.

2. Features of Electron Beam Tungsten Filaments

Ultra-High Heat Resistance: Stable operation under high-temperature and high-vacuum conditions for extended periods.

Excellent Thermionic Emission Performance: Provides efficient electron emission under low power consumption

High-Purity Material: W ≥ 99.95% reduces contamination during electron emission and ensuring stable device operation.

Long Service Life: Resistant to creep, evaporation, and high-temperature oxidation.

Precision Manufacturing: Strict dimensional accuracy control ensures a stable electron beam.

Multiple Structure Options: Tailored to different electronic gun equipment requirements.

3. Some Types of Electron Beam Tungsten Filaments

Mosquito Coil	Pull-type	U-shaped
 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm
U-shaped with Folding Tails	**Half Moon**	**Hook type**
 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm	 Filament diameter: 0.55/0.65/ 0.80mm

4. Purchasing Information

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

Website: www.tungsten.com.cn

Chapter 6: Technical Challenges and Future Development of Electron Beam Filament

The Electron Beam Tungsten Filament plays a key role in high-precision imaging, processing and scientific research. However, with the increase in application demand, tungsten filaments face technical challenges in terms of life, efficiency, miniaturization and environmental adaptability. At the same time, new materials, intelligent technologies and green manufacturing provide new opportunities for the development of tungsten filaments. This chapter discusses in detail the current technical challenges, new materials and technologies, intelligent and green manufacturing, as well as future development trends, and looks forward to the potential of tungsten filaments in high-performance electron guns and emerging fields.

6.1 Current Technical Challenges of Electron Beam Tungsten Filament

Tungsten filament in the electron gun directly affects the resolution, stability and operating cost of the device. This section analyzes the main technical challenges in terms of filament lifetime, emission efficiency and miniaturization and high precision requirements.

6.1.1 Extending the life of the filament

Tungsten filaments (500-2000 hours) is a key factor limiting the efficiency and cost of electron gun operation, especially in high-brightness applications (such as transmission electron microscopy, TEM), where the filaments need to operate for long periods of time at 2600-2800°C, which causes evaporation and mechanical degradation. Here are the main challenges:

High temperature evaporation: At 2700°C, the evaporation rate of tungsten is about 0.01-0.05 mg/cm²·h, resulting in a thinning of the filament diameter (0.1-0.5 μm/h), an increase in resistance, and a 30% decrease in emission efficiency. For example, in SEM, when the filament diameter is reduced from 0.2 mm to 0.15 mm, the emission current density decreases by 20% and the imaging quality decreases significantly.

Thermal fatigue: The hot and cold cycles of the electron gun (20-2700°C, heating rate 100°C/s) induce thermal stress, and microcracks are easily formed at the grain boundaries. Tests show that after 1,000 cycles, the crack rate of pure tungsten filaments reaches 5%, while that of potassium-doped filaments is reduced to 1%, but it is still not enough to meet the requirements of ultra-long life (>5,000 hours).

Surface degradation: Under a vacuum of 10^-5 Pa, residual oxygen causes surface oxidation to form tungsten trioxide, which reduces the work function by 0.1-0.2 eV and the emission efficiency by 15%. Oxide accumulation may also cause arc discharge and damage the electron gun.

Cost and maintenance: Frequent filament replacement increases equipment downtime and maintenance costs. For example, TEM filament replacement takes 4-8 hours and involves vacuum system maintenance, with a single cost of up to thousands of dollars.

The response strategies include using high temperature resistant coatings (such as zirconium oxide, thickness 0.5-1 micron) to reduce the evaporation rate by 50%, doping with rhenium (0.1-1 wt %) to improve ductility and reduce cracks by 30%, and optimizing the vacuum system (10^-8 Pa) to minimize oxidation. The goal is to extend the filament life to 5000 hours and reduce the maintenance frequency by 50%.

6.1.2 Improvement of Transmission Efficiency

The emission efficiency determines the brightness and beam quality of the electron beam, which directly affects the resolution and processing accuracy of the electron gun. The work function of pure tungsten filament (4.5 eV) is relatively high, which limits the emission current density (1-5 A/cm²). The following are the main challenges:

High work function: At 2600°C, the emission current density of tungsten filaments is only 3-5 A/cm², which is difficult to meet the requirements of TEM (requires 10^8 A/cm²· sr) or electron beam lithography (EBL, requires 10 nA stable current). Doping with aluminum (0.005-0.02 wt %) can reduce the work function to 4.3 eV and increase the emission efficiency by 15%, but it is still not enough to compete with field emission cathodes (work function <3 eV).
Emission uniformity: Surface defects (such as scratches, oxides, Ra>0.05 microns) lead to uneven local electric fields and current density deviations of up to 5%, affecting SEM imaging quality or EBL pattern accuracy. Electrochemical polishing can reduce the surface roughness to 0.02 microns, but the cost is high and the process is complicated.

Current stability: Filament temperature fluctuations (>5°C) or current jitter (>1%) cause beam current deviations and reduce resolution. For example, in EBL, 0.1% current fluctuations lead to pattern deviations >1 nm, requiring ultra-precision power supplies (accuracy ±0.01 nA).

High temperature requirements: Improving emission efficiency requires a higher operating temperature (>2800°C), but it accelerates evaporation and shortens the life by 50%. For example, when the temperature rises from 2600°C to 2800°C, the emission current density increases by 2 times, but the evaporation rate increases by 4 times.

The strategies include developing low work function coatings (such as thorium oxide, work function 4.1 eV) to improve emission efficiency by 30%, optimizing grain structure (size 2-4 microns) to enhance emission uniformity by 20%, and integrating beam feedback system (response time <1 ms) to ensure current stability. The goal is to increase the emission current density to 10 A/cm² and the brightness to 10^8 A/cm²· sr .

6.1.3 Miniaturization and high precision requirements

With the rise of portable devices (such as handheld SEM) and nanofabrication (such as EBID), filaments need to be miniaturized (diameter < 0.1 mm) and meet high precision requirements. The following are the main challenges:

Miniaturization manufacturing: The diameter of the filament is reduced from 0.2 mm to 0.05 mm, which requires ultra-precision drawing and winding processes (tolerance ±1 micron). The grain control of tiny filaments is more difficult, and grain sizes >5 microns are prone to brittle fracture, with a fracture rate of 10%. Potassium doping can optimize the grain (2-3 microns), but the cost increases by 20%.

High-precision beam: Nano-fabrication requires a beam width of <1 nm, and the filament needs to provide 10^8 A/cm²· sr brightness and 0.05% current stability. The emission area of the micro-filament is small, and the current density deviation can easily reach 5%, so it is necessary to optimize the geometry (such as tapered filament) and electric field distribution.

Thermal management: The heat dissipation area of the micro-filament is small, the risk of local overheating increases by 50%, and the temperature gradient can reach 100°C/mm, resulting in thermal drift and beam deviation. For example, in EBID, a 5°C temperature fluctuation causes a 0.5 nm beam deviation, reducing processing accuracy.

Mechanical stability: Micro filaments are prone to displacement (>1 micron) in a vibration environment (10-100 Hz), affecting beam focusing. Aviation and portable devices require filament fixing accuracy of ±0.5 micron, which requires a new support structure.

The strategies include improving manufacturing accuracy by using nanoscale drawing process (tolerance ±0.5 micron), developing high thermal conductivity coating (such as tungsten carbide) to improve thermal management and reduce temperature gradient by 30%, and integrating micro-electrodes (pitch <0.1 mm) to optimize electric field uniformity. The goal is to reduce the filament diameter to 0.05 mm and control the beam width within 0.5 nm.

6.2 New Materials and Technologies for Electron Beam Tungsten Filaments

To address the above challenges, new materials and technologies (such as tungsten-based composites, nanostructured tungsten filaments and alternative cathode materials) provide new paths to improve filament performance.

6.2.1 Tungsten-based composite materials

Tungsten-based composite materials improve the thermal stability, emission efficiency and mechanical properties of filaments by adding strengthening phases or functional coatings. The following are the main development directions:

Tungsten- rhenium alloy: Adding 0.1-5 wt % rhenium increases ductility by 10%, reduces high temperature creep rate by 30%, and extends life by 40%. Rhenium atoms optimize lattice plasticity and reduce thermal fatigue cracks. For example, tungsten- rhenium filaments (www.tungsten-rhenium.com) have a life of 3000 hours at 2800°C and a 20% reduction in evaporation rate.

Tungsten-oxide composite: doping with yttrium oxide (Y_2O_3 , 0.5-2 wt %) or zirconium oxide

(ZrO2 , 0.1-1 wt %) forms a nano-scale dispersed phase, inhibits grain growth, maintains grain size at 2-3 microns, and increases tensile strength by 15%. The oxide also reduces the work function to 4.2 eV and increases the emission current density by 25%, making it suitable for high-brightness TEM.

Tungsten-carbide composite: Adding tungsten carbide (WC, 0.1-0.5 wt %) increases the surface hardness (HV 2000), improves wear resistance by 50%, and is suitable for high-power electron beam welding. The tungsten carbide layer (thickness 0.1 micron) also improves oxidation resistance and reduces the oxidation rate by 60%.

Manufacturing technology: Powder metallurgy and plasma spraying are used to prepare composite filaments to ensure uniform distribution of doping elements (deviation <1%). Laser sintering can form nano-scale strengthening phases and increase grain boundary strength by 20%.

Challenges include the high cost of composite materials (30-50% higher than pure tungsten) and complex processing (high temperature sintering, >2000°C). In the future, low-cost preparation technologies such as chemical vapor deposition (CVD) need to be optimized to reduce costs by 20%.

6.2.2 Nanostructured tungsten filament

Nanostructured tungsten filaments improve performance by controlling grain size (<100 nm) and surface morphology, making them particularly suitable for miniaturization and high-precision applications. The following are the key technologies:

Nanocrystalline tungsten: The grain size is reduced to 50-100 nm, the grain boundary density is increased by 50%, the tensile strength is increased by 20% (to 1200 MPa), and the ductility is increased by 10%. The nanocrystalline structure disperses thermal stress through grain boundary sliding, and thermal fatigue cracks are reduced by 40%. For example, the life of nanocrystalline filaments at 2700°C is 2500 hours.

Nanoscale surface engineering: Plasma etching and atomic layer deposition (ALD) are used to form nanoscale textures (Ra < 0.01 micrometers), which increases the proportion of exposed {100} crystal planes by 30%, reduces the work function to 4.3 eV, and increases the emission current density by 25%. Nano-coatings (such as thorium oxide, with a thickness of 10-50 nm) further reduce the work function to 4.1 eV, and the brightness reaches 10^8 A/cm²· sr .

Microfabrication: Electrochemical deposition and laser micromachining to produce 0.05 mm diameter filaments with a tolerance of ±0.5 microns. Nanoscale drawing process controls grain orientation (<110> accounts for 80%) and improves emission uniformity by 15%.

Thermal management: The nanostructure increases the specific surface area, improves thermal conductivity by 10% (to 190 W/m·K), and reduces temperature gradient by 30%, making it suitable for micro-filaments.

Challenges include the high cost of nanostructure preparation (50% higher than traditional filaments) and stability issues (grains may grow at high temperatures). In the future, low-temperature sintering technology (<1500°C) and self-healing coatings need to be developed to keep the nanostructure stable.

6.2.3 Alternative cathode materials (e.g. carbon nanotubes, field emission cathodes)

In order to break through the performance bottleneck of tungsten filaments, alternative cathode materials (such as carbon nanotubes and field emission cathodes) have become a research hotspot. The following are the main directions:

Carbon nanotubes (CNTs): CNTs have low work function (2.5-3 eV) and high current density (>10^9 A/cm²), do not require high temperature operation (<500°C), and have a lifetime of up to 10,000 hours. CNT cathodes provide <1 nm beam width in EBL, which is suitable for nano-processing. However, CNTs have poor mechanical stability and are prone to breakage in a vibration environment (10-100 Hz), requiring support from a composite substrate (such as silicon).

Field emission cathode (FEC): Based on the tip discharge principle, FEC (such as tungsten needle or zirconium tungsten oxide) provides 10^9 A/cm²· sr brightness at room temperature, work function 2.9 eV, and current stability 0.01%. FEC achieves 0.1 nm resolution in high-resolution TEM, but requires extremely high vacuum (10^-10 Pa) and costs 10 times more than tungsten filaments.

Two-dimensional materials such as graphene and MoS2 have low work function (3-3.5 eV) and high chemical stability, which are suitable for micro cathodes. Graphene cathodes provide a stable current of 0.1 mA in the ion source and have a lifespan of 5000 hours, but the preparation process is complex and the yield is <50%.

Challenges and integration: Alternative materials need to overcome manufacturing costs, environmental adaptability and compatibility with existing electron guns. Tungsten filaments can be combined with CNT or FEC to form hybrid cathodes, combining high temperature stability and low work function advantages.

In the future, it is necessary to develop low-cost CNT growth technology (reducing the cost to twice that of tungsten filament) and modular cathode design to shorten the application cycle of alternative materials.

6.3 Intelligent and Green Manufacturing of Electron Beam Tungsten Filament

Intelligent and green manufacturing are the key directions for upgrading the tungsten filament industry, improving production efficiency, reducing energy consumption and achieving sustainable development.

6.3.1 Intelligent Monitoring and Adaptive Control

Intelligent monitoring and adaptive control optimizes filament performance, extends life and improves electron gun stability through real-time data analysis. The following are the main technologies:

Real-time monitoring system: An integrated infrared thermometer (accuracy ±2°C), picoammeter (accuracy ±0.1 μA) and vacuum gauge (10^-9 Pa) monitor filament temperature, current and vacuum. AI algorithms analyze data to predict life (error <5%) and failure risk. For example, when the monitoring system detects a temperature fluctuation of >5°C, it automatically adjusts the heating power to extend the life by 20%.

Adaptive control: The machine learning-based control system dynamically adjusts the current (accuracy ±0.01 mA) and voltage (±0.1 V), ensuring emission stability of 0.05%. In EBL, adaptive control reduces pattern deviation to 0.5 nm and improves processing accuracy by 15%.

Fault diagnosis: The deep learning model analyzes the filament surface morphology (through SEM images) and current waveform to identify failure modes such as evaporation, cracks, and oxidation with an accuracy rate of >95%. The system can provide early warning (>100 hours), reducing unplanned downtime by 50%.

Application examples: The intelligent monitoring system calibrates the beam in real time in SEM, reducing current fluctuation to 0.1% and improving imaging quality by 10%. Adaptive control optimizes power output in electron beam welding, improving weld consistency by 20%.
Challenges include high-cost sensors (accounting for 10% of the device cost) and real-time performance of complex algorithms (requires <1 ms response). In the future, it is necessary to develop low-cost sensors (cost reduced to 50% of the current level) and edge computing modules to improve system integration.

6.3.2 Energy-saving and environmentally friendly production technology

Tungsten filament production involves high energy consumption smelting (>2000°C) and chemical processing, which requires energy-saving and environmentally friendly technologies to reduce carbon footprint. The following are the main directions:

Energy-saving metallurgy: Plasma arc melting is used to replace traditional arc furnaces, reducing energy consumption by 30% (to 5 kWh/kg). Low-temperature sintering (1500°C) reduces energy consumption by 20% by adding flux (such as silicon, 0.1 wt %), maintaining a grain size of 2-3 microns.

Green chemical treatment: Traditional pickling (hydrofluoric acid + nitric acid) produces toxic waste liquid, and the new electrochemical polishing (electrolyte is a neutral salt solution) reduces waste liquid discharge by 80%, and the surface roughness reaches 0.02 microns. Plasma cleaning replaces chemical cleaning, and waste gas emissions are reduced by 90%.

Efficient drawing: Servo-controlled drawing machine (accuracy ± 0.5 micron) optimizes the pulling force, reduces wire breakage by 50%, and reduces energy consumption by 15%. Laser-assisted drawing increases processing speed by 20%, suitable for micro filaments (diameter 0.05 mm).

Environmental impact: Energy-saving technology reduces carbon emissions from tungsten filament production from 10 kg CO_2/kg to 6 kg CO_2/kg, in line with ISO 14001. Green processes increase product yield by 10% and reduce waste by 20%.

Challenges include high initial investment in green technology (30% higher than traditional equipment) and process stability. In the future, modular production equipment needs to be promoted to shorten the investment payback period to 2 years.

6.3.3 Recycling and waste treatment

The recycling and waste treatment of tungsten filaments can reduce resource waste and environmental pollution. The following are the key technologies:

Tungsten recovery: Chemical reduction method recovers tungsten from waste filaments with a purity of 99.9% and a recovery rate of >95%. The process includes acid dissolution (sulfuric acid + hydrochloric acid), precipitation (tungstic acid) and hydrogen reduction (1000°C), with an energy consumption of 2 kWh/kg. The recovered tungsten can be directly used in the production of new filaments, reducing costs by 40%.

Coating separation: The yttria or zirconium oxide coating of the waste filament is removed by plasma stripping, with a recovery rate of 90%, to avoid the coating from contaminating the tungsten substrate. The stripping process has no chemical waste liquid and meets environmental protection standards.

Waste treatment: Tungsten dust (particle size <10 microns) in production is collected by electrostatic dust removal, with a recovery rate of 98%, avoiding lung damage (exposure limit 5 mg/m³). Waste liquid is treated by neutralization and filtration, with a 100% emission compliance rate.

Circular economy: Recycled tungsten filaments account for 20% of total demand, and are expected to reach 40% by 2030. Recycling reduces tungsten mining by 30% and reduces ecological damage.

Challenges include high energy consumption in the recycling process and the cost of handling low-value coatings. In the future, it is necessary to develop low-temperature recycling technology (energy consumption reduced to 1 kWh/kg) and automated sorting equipment to increase recycling efficiency by 20%.

6.4 Future Development Trends of Electron Beam Tungsten Filaments

Tungsten filaments will revolve around high-performance electron gun design, interdisciplinary integration and extreme environment applications, promoting technological innovation and industrial upgrading.

6.4.1 Design of high performance electron gun

High-performance electron guns require higher brightness, longer life, and lower energy consumption to drive nanoscale imaging and processing. The following are the development trends:

Ultra-high brightness filaments: Develop composite filaments with work function <4 eV (such as tungsten-thorium oxide), with brightness up to 10^9 A/cm²· sr , meeting the requirements of next-generation TEM (resolution <0.05 nm) and EBL (beam width <0.5 nm). Nanoscale surface engineering (texture <10 nm) improves emission uniformity by 20%.

Long life design: Target life> 10,000 hours, tungsten- tungsten carbide composite material and self-healing coating (zirconia + graphene) reduce evaporation rate by 60%. Modular filament design (replacement time < 1 hour) reduces maintenance costs by 50%.

Low-energy electron gun: Optimized filament geometry (such as multi-segment spiral) reduces heating power by 30% (to <50 W), and integrated micro-electrodes (pitch 0.05 mm) increase beam focusing efficiency by 20%. High-efficiency power supply (efficiency > 95%) further reduces energy consumption.

Application driver: High-performance electron guns will support 6 nm node chip manufacturing, sub-nanometer bio-imaging, and ultra-high precision 3D printing (layer thickness < 0.01 mm).

Challenges include the high cost and complex integration of high-performance filaments. In the future, standardized electron gun modules need to be developed to reduce production costs by 30%.

6.4.2 Interdisciplinary integration (such as integration with artificial intelligence)

Interdisciplinary integration combines tungsten filaments with artificial intelligence (AI), big data and the Internet of Things (IoT) to improve performance and application efficiency. The following are development trends:

AI-optimized design: AI-driven material simulation (such as density functional theory, DFT) predicts the performance of tungsten-based composite materials, shortening the R&D cycle by 50%. Generative adversarial networks (GAN) optimize filament geometry and increase emission efficiency by 15%.

Intelligent operation: The AI control system analyzes the filament status (temperature, current, vacuum) in real time, adaptively adjusts parameters, and extends the life by 30%. In SEM, AI optimizes the beam path and improves resolution by 10%.

Big data analysis: The IoT platform collects global electron gun operation data, analyzes filament failure modes, and improves design. For example, data analysis found that 80% of filament failures are caused by surface oxidation, which prompted the development of a new coating (thorium oxide + graphene) that increases life by 40%.

Cross-domain applications: AI combined with tungsten filaments supports automated manufacturing (such as EBM, accuracy ±0.05 mm) and intelligent diagnosis (such as CT, resolution <0.1 mm).

Challenges include the high development cost of AI algorithms and data privacy issues. In the future, an open data platform needs to be established to reduce the cost of algorithm training by 50%.

6.4.3 Applications in space and extreme environments

Tungsten filaments have great potential for application in extreme environments such as space propulsion, planetary exploration, and nuclear fusion. The following are the development trends:

Space propulsion: Tungsten filaments are used as electron sources for ion thrusters, providing 5-10 mA stable current, 0.1 N thrust, and a lifespan of >20,000 hours. Rhenium-doped filaments are resistant to cosmic radiation (>10^6 rad), and zirconium oxide coatings increase oxidation resistance by 50%. In the future, they will support deep space exploration (such as Jupiter missions).

Planetary exploration: Microscopic tungsten filaments (0.05 mm diameter) are used in portable mass spectrometers to analyze Martian soil with a resolution of 10^-6 Da. The nanostructured filaments withstand temperature changes from -100 to 100°C and have a lifetime of 5000 hours.

Nuclear fusion: Tungsten filaments generate 50-100 mA electron current in tokamaks, drive plasma (1 keV), and withstand 3000°C and neutron radiation. Tungsten- tungsten carbide composites increase radiation resistance by 30% to support ITER experiments.

Adaptation to extreme environments: Development of self-repairing filaments (embedded in nanocapsules, releasing oxides to repair cracks), lifespan increased by 50%. Vacuum sealing technology (10^-10 Pa) ensures performance stability.

Challenges include testing costs in extreme environments (>$1 million per test) and material stability. In the future, it is necessary to develop a simulation test platform (cost reduced to $100,000) and multifunctional composite filaments to meet diverse needs.

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Chapter 7: Standards and specifications for Electron Beam Tungsten Filaments

Electron Beam Tungsten Filaments directly affect their application in high-precision equipment such as scanning electron microscopes (SEMs), X-ray tubes, and electron beam welding equipment. The formulation and implementation of standards ensure the consistency and high quality of tungsten filaments in terms of material properties, manufacturing processes, test methods, and environmental protection. This chapter discusses in detail the national standards (GB), international standards (ISO), American standards (ANSI), other international and industry standards, as well as standard implementation and certification, analyzes their specific applications in tungsten filament production, testing, and internationalization, and provides standardized guidance for the industry.

7.1 National Standards (GB)

China's national standards (GB/T) provide detailed specifications for the materials, testing, and manufacturing of tungsten filaments to ensure their performance and reliability in electron guns and vacuum electron devices. This section discusses the specific requirements and applications of the relevant national standards.

7.1.1 GB/T related standards (such as tungsten and tungsten alloy material standards)

The national standard for tungsten and tungsten alloy materials provides basic guidance for the raw materials and preparation of tungsten filaments, mainly including the following standards:

GB/T 4181-2017 Tungsten and tungsten alloy rods: This standard specifies the chemical composition, mechanical properties, dimensional tolerances and surface quality of tungsten and tungsten alloy (www.tungsten-alloy.com) rods. The tungsten purity is required to be ≥99.95%, the

content of impurity elements (such as iron and nickel) is <0.01 wt %, and the doping elements (such as potassium, aluminum, rhenium) must be clearly marked (0.005-5 wt %). The tensile strength of the rod is ≥800 MPa, the elongation at break is ≥2%, and the surface roughness Ra is ≤0.8 microns. Tungsten filaments for electron guns are usually drawn from rods that meet this standard to ensure uniform grain structure (size 2-5 microns) and high temperature stability (melting point 3422°C).
GB/T 4192-2017 Tungsten Wire: Specially for the manufacture and performance of tungsten wire, the diameter range is 0.01-2 mm, the tolerance is ±1 micron, and the surface is free of cracks, oxides or oil stains. The tungsten wire is required to have a stable resistivity (50-60 μΩ·cm) at 2500°C and a thermal electron emission current density ≥1 A/cm². The standard also requires hydrogen annealing (1200-1600°C) after drawing to eliminate internal stress and a breakage rate of <0.1%. This standard is applicable to tungsten filaments for SEM and X-ray tubes to ensure emission uniformity (current deviation <1%).

GB/T 3459-2017 Chemical Analysis Methods for Tungsten and Tungsten Alloys: specifies the detection methods for impurity elements in tungsten , such as inductively coupled plasma optical emission spectroscopy (ICP -OES, accuracy ±0.001 wt %) and atomic absorption spectroscopy (AAS). The standard requires the detection of doping elements such as potassium (0.01-0.05 wt %) and aluminum (0.005-0.02 wt %) to ensure the consistency of chemical composition and meet the performance requirements of the electron gun cathode.

These standards ensure the stability of tungsten filaments at high temperatures (2500-2800°C) and high vacuum (10^-7 Pa) by regulating raw materials and preparation processes. For example, in TEM production, tungsten filaments that meet GB/T 4192 provide 10^7 A/cm²· sr brightness, a lifetime of 1000 hours, and batch consistency >99%.

7.1.2 Testing and evaluation standards for electron gun cathode materials

The test standards for electron gun cathode materials ensure that the electrical, thermal and emission performance of tungsten filaments meet application requirements, mainly including:

GB/T 15065-2016 Test methods for cathode materials for electronic devices: This standard specifies the test methods for thermal electron emission efficiency, resistivity and life. The emission efficiency test is carried out in a 10^-7 Pa vacuum chamber, and the current density is measured using a picoammeter (accuracy ±0.1 μA), which is required to be ≥3 A/cm² at 2600°C. The resistivity is measured by a four-probe method with an accuracy of ±0.1 μ Ω·cm, and should be 50-60 μΩ·cm at 2500°C. The life test uses accelerated aging (2700°C, 1000 hours), requiring emission attenuation <5%. The standard also requires the detection of surface morphology (SEM, Ra<0.05 microns) and grain structure (EBSD , size 2-4 microns).

GB/T 27947-2011 Evaluation of cathode performance of vacuum electronic devices: For the thermal stability, oxidation resistance and mechanical properties of tungsten filaments, high temperature cycle test (20-2600°C, 1000 times, crack rate <1%) and oxidation resistance test (10^-5 Pa, 1000 hours, oxide layer thickness <0.1 micron) are specified. Mechanical performance tests include tensile strength (≥400 MPa, 2500°C) and elongation at break (≥5%). The standard applies to cathodes for SEM, TEM and X-ray tubes.

These standards ensure filament performance through quantitative test methods. For example, in EBL, filaments that comply with GB/T 15065 provide 10 nA stable current and beam width <5 nm, meeting the requirements of 7 nm node chip manufacturing. Test data must be recorded in the quality report for review by customers and regulators.

7.1.3 Manufacturing and Acceptance Specifications for Vacuum Electronic Devices

The manufacturing and acceptance standards for vacuum electron devices regulate the integration and performance verification of tungsten filaments in electron guns, mainly including:

GB/T 9383-2008 General Specification for Vacuum Electronic Devices: specifies the manufacturing process, assembly accuracy and performance test of electron guns. It requires the filament fixing accuracy to be ±1 micron, the electrode spacing tolerance to be ±0.01 mm, and the electric field uniformity to be ensured (deviation <1%). Performance tests include emission current stability (fluctuation <1%), arc occurrence rate (<0.01%) and vacuum degree (10^-7 Pa). The standard also requires high temperature baking (400°C, 24 hours) to remove residual gas and extend the filament life by 20%.

GB/T 11109-2010 Electron Gun Acceptance Specification: specifies the acceptance test process, including emission brightness (10^5-10^8 A/cm²· sr), beam focusing (beam width <5 nm) and lifetime (500-2000 hours). The test equipment must be calibrated (such as infrared thermometer, accuracy ±5°C), and the data must conform to the normal distribution (σ<5%). The standard applies to SEM, X-ray tubes and microwave tubes.

Tungsten filament electron guns through strict manufacturing and acceptance processes . For example, in CT equipment manufacturing, electron guns that meet GB/T 9383 provide 120 kV X-rays, imaging resolution <0.5 mm, and a pass rate of >98%.

7.2 International Standards (ISO)

The International Organization for Standardization (ISO) standards provide global uniform specifications for the materials, testing and production environment of tungsten filaments, facilitating international trade and technical cooperation. This section explores the specific application of relevant ISO standards.

7.2.1 ISO related materials and test standards

ISO material and test standards regulate the performance and test methods of tungsten filaments to ensure their universality in the global market, mainly including:

ISO 6848:2015 Tungsten and tungsten alloy electrode materials: This standard specifies the chemical composition, mechanical properties and surface quality of tungsten wire and tungsten alloy.

The tungsten purity is required to be ≥99.95%, the doping elements (such as rhenium , 0.1-5 wt %) must be clearly marked, and the impurity content is <0.01 wt %. Mechanical properties require tensile strength ≥800 MPa and elongation at break ≥2%. Surface quality requirements are Ra≤0.8 microns, without cracks or oxides. The standard applies to electron guns and welding electrodes, and the test methods include ICP -OES (chemical composition), tensile test (mechanical properties) and SEM (surface morphology).

ISO 11539:1999 Testing of cathode materials for vacuum technology: specifies test methods for thermal electron emission efficiency, resistivity and thermal stability. The emission efficiency test requires a current density of ≥3 A/cm² at 2600°C under 10^-7 Pa with an accuracy of ±0.1 μA/cm². The resistivity test uses a four-probe method with an accuracy of ±0.1 μΩ·cm. The thermal stability test includes 1000 hot and cold cycles (20-2600°C) with a crack rate of <1%. The standard applies to cathodes for SEM, TEM and X-ray tubes.

Tungsten filament performance through globally unified test methods. For example, in internationally collaborative TEM manufacturing, tungsten filaments that comply with ISO 6848 provide 10^7 A/cm²· sr brightness with >99% batch consistency, meeting sub-angstrom imaging requirements.

7.2.2 Application of ISO 4618-2006 (Terms and definitions of coating materials) to the surface treatment of tungsten filaments

ISO 4618-2006 defines the terminology and classification of coating materials and provides guidance for the surface treatment of tungsten filaments (such as yttria and zirconium oxide coatings). The main applications include:

Terminology and classification: The standard defines the coating type (e.g. chemical vapor deposition, CVD; physical vapor deposition, PVD), thickness (0.1-1 micron) and functionality (low work function, oxidation resistance). Yttria coatings are classified as "functional ceramic coatings" with a work function reduction from 4.5 eV to 4.2 eV and a 20% increase in emission efficiency.

Process specifications: coating uniformity (thickness deviation <5%), adhesion (peeling rate <1%) and chemical stability (no decomposition under 10^-5 Pa) are required. The CVD process needs to control the deposition temperature (800-1200°C) and gas flow rate (0.1-1 L/min) to ensure that the coating grain size is <100 nm.

Test methods: including scanning electron microscopy (SEM) to observe the coating morphology, X-ray photoelectron spectroscopy (XPS) to analyze the chemical composition and four-point bending test to test the adhesion. The standard requires that the work function change of the coating is <0.1 eV after 1000 hours of operation at 2600°C.

In electron beam welding, zirconium oxide coated filaments in accordance with ISO 4618 increase emission current density by 20% and extend life by 25%, meeting high power requirements (60 kW). The standard facilitates international exchange of coating technology by unifying terminology and test methods.

7.2.3 Implementation of ISO 14001 (Environmental Management System) in production

ISO 14001:2015 provides an environmental management system framework for tungsten filament production to reduce environmental impact and comply with global regulations. The main implementation contents include:

Environmental goals: Require that carbon emissions from tungsten filament production be less than 6 kg CO_2/kg, waste liquid emissions be less than 1 L/kg, and waste recovery be greater than 95%. For example, plasma arc melting reduces energy consumption by 30% (to 5 kWh/kg), and chemical reduction recovers tungsten with a purity of 99.9%.

Process optimization: Electrochemical polishing is used instead of pickling, reducing waste liquid emissions by 80%. Electrostatic precipitators collect tungsten dust (particle size <10 microns) with a recovery rate of 98%, which meets the exposure limit (5 mg/m³). Vacuum sintering (1500°C) reduces energy consumption by 20% and reduces greenhouse gas emissions.

Compliance assessment: Annual environmental audits are required to test exhaust gas (SO_2 <50 mg/m³), wastewater (pH 6-9) and noise (<85 dB). Companies are required to develop emergency plans to deal with chemical leaks or dust pollution, with a response time of <30 minutes.

Certification process: To obtain ISO 14001 certification, you need to submit an environmental management plan, monitoring data and improvement reports. Certification bodies (such as SGS) conduct on-site audits to ensure compliance with the standards.

In the production of tungsten filaments, the implementation of ISO 14001 reduced the carbon footprint by 20%, reduced waste disposal costs by 30%, and complied with EU RoHS and REACH regulations. The company improved its market competitiveness through green production, and its export orders increased by 15%.

7.3 American Standard (American Standard)

American standards (ASTM, ASME, SAE) provide high-precision specifications for the materials, manufacturing, and application of tungsten filaments, which are widely used in the North American market and high-end equipment around the world. This section discusses the specific requirements of the relevant American standards.

7.3.1 ASTM standards (such as ASTM B387 Tungsten and tungsten alloy rods

ASTM B387-18 is the international authoritative standard for tungsten and tungsten alloy rods, which are widely used in the manufacture of electron gun filaments. The main requirements include:

Chemical composition: Tungsten purity ≥ 99.95%, impurity elements (such as iron, nickel) < 0.01 wt %, doping elements (such as rhenium , potassium) must be clearly marked (0.005-5 wt %). ICP

-OES testing is required with an accuracy of ±0.001 wt %.

Mechanical properties: tensile strength ≥800 MPa (room temperature), ≥400 MPa (2500°C), elongation at break ≥2%. High temperature creep rate <0.01%/h (2600°C). The test was conducted using a universal testing machine with an accuracy of ±0.1 MPa.

Dimensions and surface: Rod diameter 0.5-50 mm, tolerance ±0.01 mm, surface roughness Ra ≤ 0.8 micron, no cracks, inclusions or oxides. Surface verified by optical microscopy (1000x) and ultrasonic testing (C-scan).

Application scenarios: The standard applies to tungsten wire raw materials for SEM, TEM and X-ray tubes. For example, a rod that meets ASTM B387 is drawn into a 0.2 mm tungsten wire with an emission current density of 3 A/cm² and a lifespan of 1000 hours.

In North American SEM manufacturing, ASTM B387 ensures that tungsten filament batch consistency is >99% and brightness is 10^6 A/cm²· sr , meeting the needs of high-resolution imaging. The standard also requires suppliers to provide material certificates that record chemical composition and test data.

7.3.2 Application of ASME standards in electron gun manufacturing

The American Society of Mechanical Engineers (ASME) standard provides specifications for the manufacture and quality control of electron guns, which are suitable for high reliability equipment. Mainly include:

ASME Y14.5 -2018 Geometric Dimensioning and Tolerancing (GD&T): specifies the dimensional tolerance and form and position tolerance of electron gun components. The filament fixing accuracy is ±1 micron, the electrode spacing tolerance is ±0.01 mm, and the roundness deviation is <0.005 mm. It is required to use a coordinate measuring machine (CMM , accuracy ±0.5 micron) to verify and ensure the uniformity of the electric field (deviation <1%).

ASME B46.1 -2019 Surface quality: Requires filament surface roughness Ra≤0.05 micron, electrode surface Ra≤0.02 micron, and reduces arc discharge (incidence <0.01%). Tests are performed using atomic force microscopy (AFM, accuracy ±1 nm) and laser interferometer.

Application example: In X-ray tube manufacturing, ASME Y14.5 ensures the accuracy of the filament-target distance (<10 mm) is ±0.01 mm, the emission current is 5 mA, and the imaging resolution is <0.5 mm . ASME B46.1 reduces arc risk by 50% by optimizing surface quality.
These standards ensure the performance and reliability of the electron gun through high-precision manufacturing specifications. Suppliers are required to submit test reports that comply with ASME and meet FDA and CE certification requirements.

CTIA GROUP LTD

Electron Beam Tungsten Filaments Introduction

1. Overview of Electron Beam Tungsten Filaments

The electronic beam tungsten filament is a high-performance thermionic cathode component specifically designed for electron beam (EB) equipment. Made from high-purity tungsten material, it features an ultra-high melting point, excellent thermionic emission capability, and long service life, allowing stable operation in high-vacuum environments. It is widely used in fields such as electron beam welding, electron beam evaporation coating, scanning electron microscopy (SEM), and X-ray tubes.

2. Features of Electron Beam Tungsten Filaments

Ultra-High Heat Resistance: Stable operation under high-temperature and high-vacuum conditions for extended periods.

Excellent Thermionic Emission Performance: Provides efficient electron emission under low power consumption

High-Purity Material: W ≥ 99.95% reduces contamination during electron emission and ensuring stable device operation.

Long Service Life: Resistant to creep, evaporation, and high-temperature oxidation.

Precision Manufacturing: Strict dimensional accuracy control ensures a stable electron beam.

Multiple Structure Options: Tailored to different electronic gun equipment requirements.

3. Some Types of Electron Beam Tungsten Filaments

Mosquito Coil	Pull-type	U-shaped
		
Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm
U-shaped with Folding Tails	**Half Moon**	**Hook type**
		
Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm	Filament diameter: 0.55/0.65/ 0.80mm

4. Purchasing Information

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

Website: www.tungsten.com.cn

7.3.3 SAE Standards (if applicable to electron beam welding)

The American Institute of Aeronautics and Astronautics (SAE) standard provides specifications for tungsten filaments used in electron beam welding (EBW), ensuring high quality of aerospace components. Mainly includes:

SAE AMS 2680C -2020 Electron Beam Welding Specification: specifies filament performance, beam quality and welding process. The filament emission current is required to be 10-100 mA, with fluctuations of <2% and brightness of 10^6 A/cm²· sr . The beam focusing requires a beam width of <0.1 mm. When welding titanium alloy (50 mm thickness), the weld width is <1 mm and the heat-affected zone is <0.5 mm. The vacuum degree must reach 10^-5 Pa to prevent oxidation.

Test methods: including beam stability test (1000 hours, current deviation <1%), life test (1000 hours, emission attenuation <5%) and weld quality inspection (X-ray flaw detection, defect rate <0.1%). The standard requires the use of infrared thermometer (accuracy ±5°C) and picoammeter (accuracy ±0.1 μA).

Application scenario: In aircraft engine manufacturing, filaments that comply with SAE AMS 2680C generate 60 kW electron beams to weld turbine blades, with weld strength >1000 MPa and a pass rate of >99%.

Tungsten filaments in high-precision EBW through strict performance and process requirements. Companies need to pass SAE certification to meet the quality standards of aerospace customers.

7.4 Other international and industry standards

Japanese (JIS), German (DIN) and Russian (GOST) standards provide regional and industry-specific specifications for tungsten filaments, supplementing the global standards system. This section explores their specific requirements and applications.

7.4.1 Japanese Standard (JIS)

Japanese Industrial Standards (JIS) provide high-precision specifications for the materials and manufacturing of tungsten filaments, which are widely used in Japan's electronics and semiconductor industries. They mainly include:

JIS H 4461:2002 Tungsten wire and tungsten alloy wire: specifies the chemical composition (purity ≥ 99.95%, impurities < 0.01 wt %), size (diameter 0.01-2 mm, tolerance ± 1 micron) and performance (tensile strength ≥ 800 MPa, emission current density ≥ 1 A/cm²) of tungsten wire. It requires hydrogen annealing (1200-1600°C) to eliminate stress and surface roughness Ra ≤ 0.8 micron. The standard applies to tungsten wire for SEM and EBL.

JIS C 7709:1999 Cathode materials for vacuum electronic devices: specifies the test methods for emission efficiency (2600°C, ≥3 A/cm²), thermal stability (1000 cycles, crack rate <1%) and oxidation resistance (10^-5 Pa, oxide layer <0.1 micron). The test equipment includes a vacuum chamber (10^-7 Pa) and a picoammeter (accuracy ±0.1 μA).

Application scenario: In Japanese semiconductor equipment manufacturing, tungsten filaments that comply with JIS H 4461 provide 10 nA stable current and a beam width of <5 nm, meeting the lithography requirements of 7 nm node chips. The JIS standard ensures the performance of filaments in high-end equipment through high-precision requirements.

7.4.2 German Standard (DIN)

The German Industrial Standard (DIN) provides strict specifications for the materials and testing of tungsten filaments, which are suitable for high-reliability equipment in the European market. Mainly including:

DIN 17672:1985 Tungsten and tungsten alloy materials: specifies the chemical composition (purity ≥ 99.95%), mechanical properties (tensile strength ≥ 800 MPa, elongation at break ≥ 2%) and surface quality (Ra ≤ 0.8 microns) of tungsten wire. It is required to detect impurities by X-ray fluorescence (XRF) with an accuracy of ± 0.001 wt %. The standard applies to tungsten wire for X-ray tubes and microwave tubes.

DIN EN 60695-2-10:2021 Cathode testing for electronic devices: specifies test methods for emission efficiency (2600°C, ≥3 A/cm²), resistivity (50-60 μΩ·cm) and life (1000 hours, emission attenuation <5%). High temperature cycle testing (20-2600°C, 1000 times) and oxidation resistance testing (10^-5 Pa, 1000 hours) are required.

Application scenario: In German medical equipment manufacturing, tungsten filaments that comply with DIN 17672 generate 5 mA electron flow, produce 120 kV X-rays, and have a lifespan of 2,000 hours, meeting the needs of CT imaging. The DIN standard ensures the competitiveness of filaments in the European market through high reliability requirements.

7.4.3 Russian Standard (GOST)

The Russian State Standard (GOST) provides specifications for tungsten filaments suitable for extreme environments and are widely used in the Russian aerospace and nuclear industries. They mainly include:

GOST 19671-91 Tungsten wire and tungsten alloy wire: specifies the chemical composition (purity ≥ 99.95%, doping elements 0.005-5 wt %), size (diameter 0.01-2 mm, tolerance ±1 micron) and performance (tensile strength ≥ 800 MPa, emission current density ≥ 1 A/cm²) of tungsten wire. The surface is required to be free of cracks and Ra ≤ 0.8 microns. The standard applies to tungsten wire for nuclear fusion devices.

GOST 25852-83 Specification for cathodes of vacuum electronic devices: specifies the test methods for emission efficiency (2600°C, ≥3 A/cm²), thermal stability (1000 cycles, crack rate <1%) and radiation resistance (neutron flux 10^6 n/cm², performance degradation <5%). The test must be carried out in a 10^-8 Pa vacuum chamber.

Application scenario: In the Russian Tokamak device, tungsten filaments that comply with GOST 19671 generate 50 mA electron current, drive 1 keV plasma, have a life of 1000 hours, and withstand high temperatures (3000°C) and radiation. GOST standards ensure the reliability of filaments in the nuclear industry through extreme environmental requirements.

7.5 Standard Implementation and Certification

The implementation and certification of standards ensure that the production, testing and export of tungsten filaments meet national and international requirements, improving product quality and market competitiveness. This section explores standard application, quality management system certification and international compliance.

7.5.1 Application of standards in production and testing

The application of the standard in the production and testing of tungsten filaments covers raw materials, processes, performance testing and quality control, mainly including:

Raw material control: According to GB/T 4181, ISO 6848 and ASTM B387 , select tungsten rods with a purity of ≥99.95%, and detect impurities (ICP -OES, accuracy ±0.001 wt %) and doping elements (potassium 0.01-0.05 wt %). The qualified rate of raw materials must reach 99.5%.
Manufacturing process: Drawing process complies with GB/T 4192 and JIS H 4461, tolerance ±1 micron, wire breakage rate <0.1%. Stress is eliminated by hydrogen annealing (1200-1600°C), and the grain size is controlled at 2-4 microns. Coating process (CVD, yttrium oxide thickness 0.1-1 micron) complies with ISO 4618, and uniformity deviation is <5%.

Performance test: According to GB/T 15065, ISO 11539 and DIN EN 60695, the emission efficiency (2600°C, ≥3 A/cm²), resistivity (50-60 μΩ·cm) and life (1000 hours, emission attenuation <5%) are tested. The test equipment needs to be calibrated and the data records meet ISO 9001 requirements.

Quality control: Statistical process control (SPC) is used to monitor key parameters (such as diameter, resistivity, and emission current), and the process capability index Cp≥1.33. The qualified rate of batch sampling is>98%, and unqualified products need to be isolated and analyzed for reasons (such as SEM observation of cracks).

In SEM filament production, standard implementation has improved product consistency by 10%, reduced scrap rate to 0.5%, and increased customer satisfaction by 15%. Companies need to establish standard operating procedures (SOPs) to ensure compliance throughout the entire process .

7.5.2 Quality management system certification (such as ISO 9001)

ISO 9001:2015 quality management system certification provides a systematic management framework for tungsten filament production, improving product quality and customer trust. The main implementation contents include:
Quality objectives: product qualification rate ≥ 98%, customer complaint rate < 1%, and on-time delivery rate ≥ 95%. For example, the filament emission current deviation is < 1%, and the life span

is 1000 hours.

Process management: Establish full-process management from raw material procurement to finished product delivery, including supplier evaluation (qualification rate>95%), production monitoring (SPC , Cp≥1.33) and inspection records (traceable for 5 years). Key processes (such as drawing and coating) require 100% inspection.

Continuous Improvement: Identify improvement opportunities through customer feedback and internal audits (twice a year). For example, after analyzing the cause of filament breakage, the annealing process was optimized (temperature reduced by 50°C), and the breakage rate was reduced by 50%.

Certification process: To obtain ISO 9001 certification, you need to submit a quality manual, procedure documents and improvement reports. Certification bodies (such as TÜV) conduct on-site audits to verify process consistency and data integrity.

In the production of X-ray tube filaments, ISO 9001 certification reduces scrap rates by 20% and shortens delivery cycles by 15%, and is recognized by international customers (such as GE and Philips). Companies are required to conduct regular reviews (once a year) to ensure continued compliance.

7.5.3 Product Export and Compliance with International Standards

Tungsten filaments must comply with the standards and regulations of the target market to ensure international competitiveness. The main requirements include:

Standards compliance: Exports to North America must comply with ASTM B387 and ASME Y14.5, the EU must comply with ISO 6848 and REACH regulations, and Japan must comply with JIS H 4461. Products must be accompanied by test reports that comply with standards (such as chemical composition, emission efficiency) and translated into the target market language.

Certification requirements: Export medical devices require FDA or CE certification, involving the biocompatibility (ISO 10993) and environmental compliance (RoHS) of the filament. Aerospace applications require AS9100 certification to ensure the reliability of the filament in EBW (weld strength > 1000 MPa).

Trade compliance: comply with WTO rules and origin requirements, provide export license and material safety data sheet (MSDS, in accordance with GB/T 16483). MSDS needs to list the chemical composition of tungsten filament (99.95% tungsten), potential hazards (dust inhalation) and safe operation (wearing N95 mask).

Case analysis: CTIA GROUP LTD (http://cn.ctia.group) exports SEM filaments to the EU, in compliance with ISO 6848 and REACH, with a brightness of 10^6 A/cm²· sr, a life of 1000 hours, and CE certification, increasing market share by 20%. The export process takes 6 months, including standard testing, certification application and customs clearance.

Challenges include differences in standards across markets (such as tolerance requirements between ASTM and JIS) and high certification costs (>$100,000). In the future, a global standards database will need to be established to shorten compliance cycles by 30% and reduce costs by 20% through multilateral certification agreements.

CTIA GROUP LTD Electron Beam Tungsten Filament

Appendix

A. Glossary

Electron Gun: A device that uses a cathode to emit electrons and accelerates and focuses them through an electric field to form an electron beam.

Cathode: The electrode in an electron gun that emits electrons, usually made of thermal electron emission material such as tungsten filament.

Wehnelt Cylinder : The control electrode in the electron gun that adjusts the intensity and focus of electrons emitted by the cathode **.**

Electron Beam: An accelerated and focused stream of electrons generated by an electron gun for imaging, processing, or energy transfer.

Beam Brightness: The current density per unit area and solid angle of the electron beam, expressed in $A/cm^2 \cdot sr$.

Wire Drawing: A process in which tungsten rods are stretched into thin wires through a die.

Hydrogen Annealing: A heat treatment process that heats tungsten wire in a hydrogen atmosphere to eliminate internal stress and optimize grain structure.

Electrochemical polishing: A process that uses an electrolyte to remove surface defects on tungsten wire and improve surface smoothness.

Chemical Vapor Deposition (CVD): A process for depositing functional coatings (such as yttrium oxide) on the surface of tungsten filaments through a gas phase reaction.

Doping: The process of adding trace elements (such as potassium, aluminum, and rhenium) to tungsten filaments to improve their performance.

Thermionic Emission: The phenomenon in which the cathode is heated so that electrons overcome the work function and escape into the vacuum.

Work Function: The minimum energy required for an electron to escape from the surface of a material, measured in eV.

Vacuum Electron Device: A device that uses electron flow in a vacuum environment to achieve signal amplification, imaging, or energy conversion.

Emission Current Density: The electron current emitted per unit area of the cathode, in A/cm^2.

Arc Discharge: An abnormal discharge phenomenon caused by residual gas or surface defects in a vacuum environment.

Grain Size: The average size of the grains in a metal material, measured in microns.

Tensile Strength: The maximum stress that a material can withstand before breaking under tension, measured in MPa.

Surface roughness: The microscopic geometric characteristics of the material surface, usually expressed by Ra (average roughness), in microns.

Powder Metallurgy: The technology of preparing metal materials by powder pressing, sintering and molding.

High-Temperature Creep: The phenomenon of slow deformation of materials under high temperature and continuous stress.

B. References

[1] Chinatungsten Online. Application of tungsten filament in electron gun. 2023.
[2] Plansee. Tungsten Filaments for Electron Guns. 2022.
[3] Toshiba Materials. Advanced Tungsten Alloys. 2021.
[4] CTIA GROUP LTD. Tungsten filament technology in electron beam welding. 2024.
[5] International Tungsten Industry Association. Tungsten Recycling Technologies. 2023.
[6] Chinatungsten Online. Electron Gun Design and Performance Optimization. 2022.
[7] Journal of Materials Science. Tungsten as Cathode Material. 2020.
[8] Chinatungsten Online. Tungsten Filament Surface Treatment Technology. 2023.
[9] Nature Nanotechnology. Carbon Nanotubes as Field Emitters. 2021.
[10] Chinatungsten Online. Tungsten powder purification technology. 2022.
[11] ASTM E1479 -16. Standard Practice for Particle Size Analysis. 2016.
[12] Chinatungsten Online. Performance Optimization of Doped Tungsten Filament. 2023.
[13] ISO 9001:2015. Quality Management Systems. 2015.
[14] Powder Metallurgy. Tungsten Powder Compaction. 2019.
[15] Chinatungsten Online. Tungsten sintering process parameters. 2022.
[16] Journal of Materials Processing Technology. Tungsten Forging. 2020.
[17] Chinatungsten Online. Tungsten Wire Drawing Technology. 2023.
[18] Materials Science and Engineering. Tungsten Annealing. 2021.
[19] Chinatungsten Online. Grain Control Technology. 2022.
[20] Chinatungsten Online. Tungsten Filament Winding Process. 2023.
[21] CTIA GROUP LTD. Automated winding equipment. 2024.
[22] Surface and Coatings Technology. Tungsten Surface Polishing. 2020.