Tungsten Alloy Rod Encyclopedia

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

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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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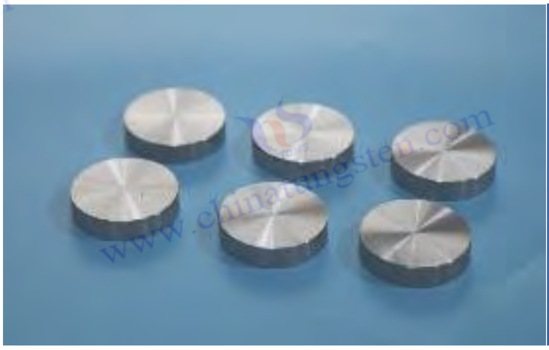
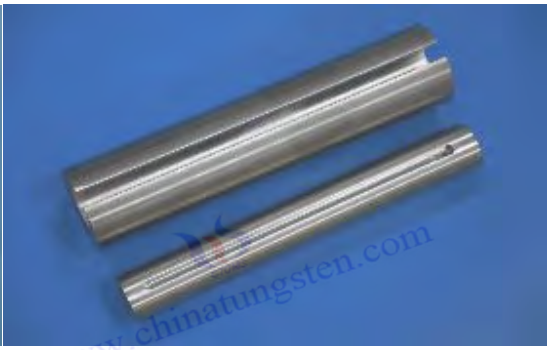

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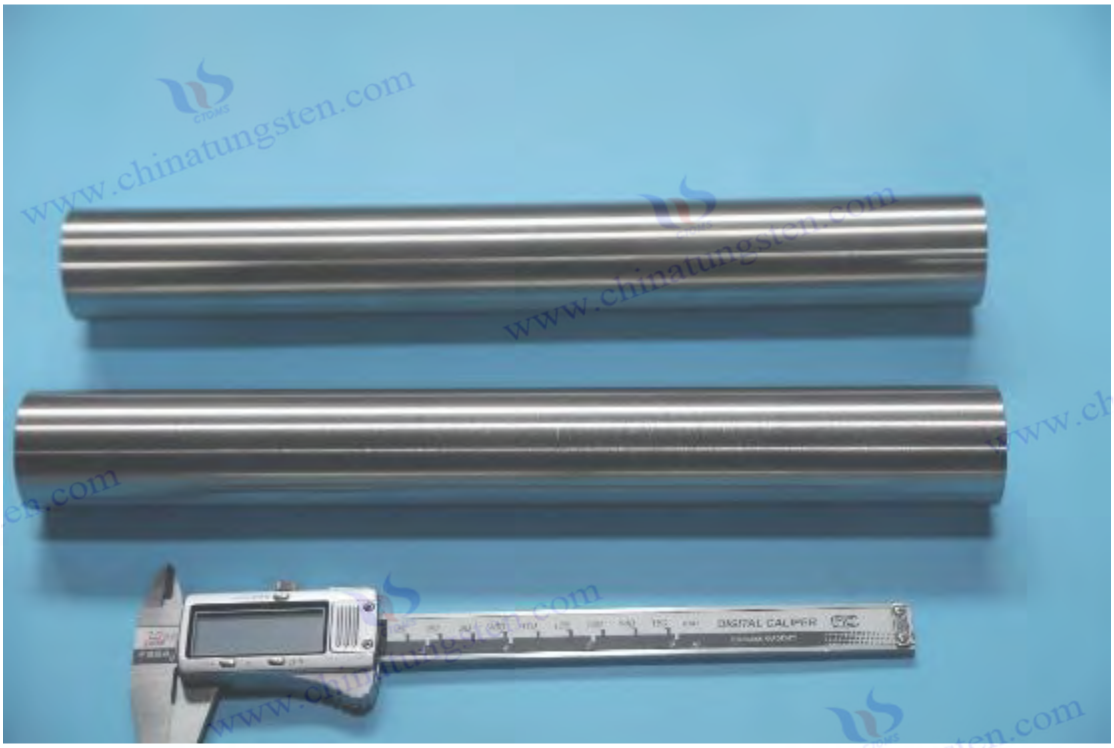

Preface

With the development of new material technology and the rapid rise of high-end manufacturing industry, high-performance functional alloy materials have become an important foundation for supporting the progress of aerospace, precision manufacturing, national defense equipment, energy systems and medical equipment. Tungsten, as one of the metals with the highest melting point in the periodic table, has high density, high hardness, high melting point and excellent radiation resistance, which makes it show unique advantages in extreme environments. Among many tungsten-based materials , tungsten heavy alloy rods have gradually become a key component in the strategic functional material system due to their unique physical properties, forming stability and wide adaptability.

Tungsten alloy rods are usually made of tungsten (W) as the main element, and are formed by adding nickel (Ni), iron (Fe), copper (Cu) and other metals to form high-density tungsten alloys (High Density Tungsten Alloy), which are prepared by powder metallurgy. Its density can reach 17.0-18.8 g/cm³, which is much higher than common metals such as steel, copper, and aluminum. It is an engineering material with high strength, good machinability and excellent service stability. With the increasing demand for compact structure, energy control accuracy and long life of equipment, the design and application of tungsten alloy rods are constantly developing in the direction of high density, high uniformity and high purity.

Tungsten alloy rod products are not only used in traditional counterweight scenarios, such as aircraft balance, aerospace attitude adjustment, shipboard inertial modules, etc., but are also widely used in bulletproof protection, radiation protection, nuclear energy components, kinetic weapons, medical

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equipment radiotherapy modules, X-ray shielding devices, gyroscope inertial rotors, electric vacuum device anode structures, electronic packaging thermal control components and other strategic technology fields. Especially in precision-guided munitions, hypervelocity armor-piercing projectiles, high-energy physics experiments and deep space exploration projects, tungsten alloy rods have become irreplaceable high-performance component materials due to their structural stability and inertial response accuracy.

At present, the global tungsten resources are extremely concentrated. China, Russia, Kazakhstan, Portugal and other countries have the main mineral resources. Among them, China ranks first in the world in terms of proven reserves, concentrate production and deep processing capacity of tungsten ore. This provides a solid raw material guarantee foundation for the design, development and process innovation of tungsten alloy rod products in China. At the same time, with the rapid upgrading of the mid-to-high-end equipment manufacturing industry, domestic tungsten alloy rods have gradually replaced imported products, achieved technological breakthroughs in key fields such as aerospace, medical nuclear engineering, and electronic countermeasures, and formed mass supply capabilities.

However, despite the increasing maturity of the tungsten alloy rod technology system, it still faces several challenges, including: how to further improve the sintering density and organizational uniformity, how to develop special-shaped rod preparation technology suitable for complex structural requirements, how to balance the material ratio of high strength and machinability, and how to reduce manufacturing energy consumption and improve recycling rate. In order to solve the above problems, a series of new process paths and advanced manufacturing methods have emerged in recent years, such as liquid phase sintering densification, micro-alloy element optimization, hot isostatic pressing (HIP) technology, multi-scale simulation design, 3D printing tungsten alloy structural parts, etc., which have injected new vitality into the high-end, functional and intelligent development of tungsten alloy rods.

This book "Encyclopedia of Tungsten Alloy Rods" was compiled under this background. The book systematically sorts out the material basis, preparation process, performance evaluation, standard system, application expansion and future trend of tungsten alloy rods, aiming to provide a detailed and practical professional reference for engineers, researchers, college teachers and students, and strategic procurement personnel engaged in tungsten alloy material research and development, product design, process optimization and industrial application.

In the process of writing this book, we have extensively referred to domestic and foreign research literature, enterprise application cases, national and industry standards, and combined with the practical experience of CTIA GROUP LTD and its partners in the field of tungsten alloys for many years, striving to make the content authoritative, the structure systematic, the language popular, and the text and pictures rich. In terms of format, the book is divided into ten chapters and multiple appendices, covering the basic concepts of tungsten alloy rods, physical and mechanical properties, powder metallurgy and forming technology, testing and quality control methods, typical application fields, international standard system, packaging and transportation specifications, market pattern analysis and cutting-edge technology trends, and attached with term indexes and reference maps for readers to consult and apply in engineering.

We hope that this book is not only a material technology reference manual, but also a bridge between the engineering application and scientific research and development of tungsten alloy rods. Whether you are a university researcher, an engineer in a tungsten product company, or an industrial design decision maker, you can get theoretical inspiration, case reference and practical guidance from it.

Due to the wide range of content and the large amount of information, there are inevitably deficiencies and omissions in the book. I sincerely ask readers to criticize and correct me.

CTIA GROUP LTD
July 2025

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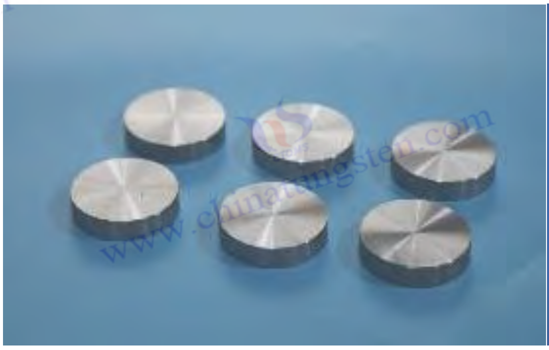
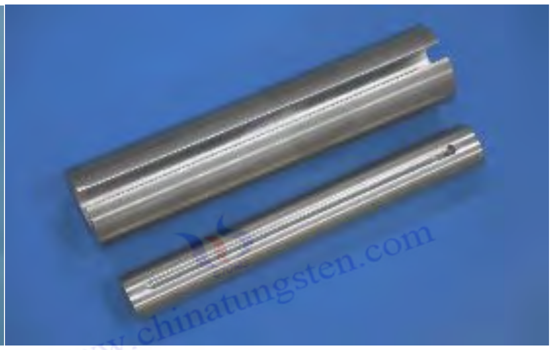

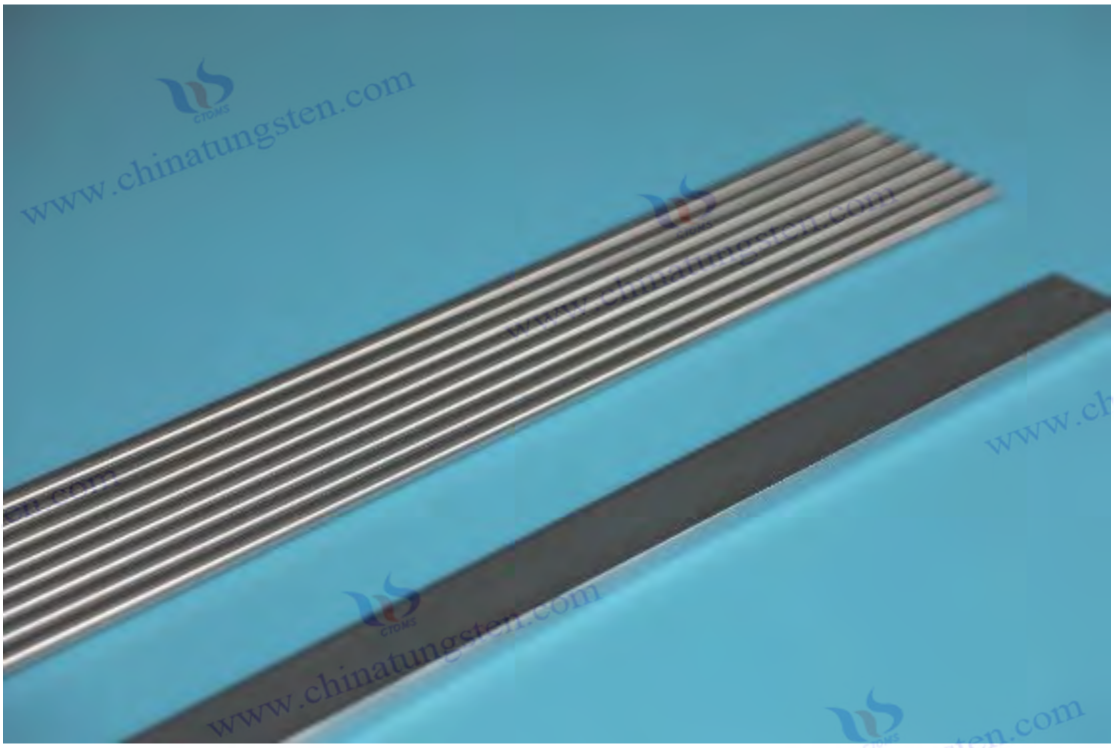

Chapter 1 Basic Concepts and Classification of Tungsten Alloy Rods

1.1 Definition and basic form of tungsten alloy rod

Tungsten alloy rods usually refer to long strips of metal materials made by powder metallurgy with tungsten (W) as the main component and a certain proportion of bonding metals such as nickel (Ni), iron (Fe), copper (Cu), etc. This type of rod has extremely high density (generally between 17.0-18.8 g/cm³), excellent mechanical properties (tensile strength can reach 700-1200 MPa), good heat resistance and corrosion resistance, and is widely used in aerospace, military equipment, nuclear energy engineering, medical equipment, electronic and electrical and other high-end fields.

tungsten alloy rods is that they have good processability and dimensional stability while maintaining high strength. Compared with traditional structural materials such as lead, steel, titanium, copper, etc., tungsten alloy rods have higher specific gravity and durability, and show irreplaceable technical value in the fields of inertial counterweights, protective shielding, precision accessories, etc.

In terms of basic form, tungsten alloy rods mainly exist in the following types:

- **Round Rod** : The most common form, suitable for a variety of uses such as rotating inertia components, gyro rotors, electrodes, and balance weights. The diameter can range from 1 mm to 100 mm, and the length is usually between 50 mm and 1500 mm. It can be cut or turned according to needs.

- **Square Rod/Rectangular Rod** : Used for processing parts with specific requirements on cross-sectional shape, commonly found in electronic packaging brackets, high-temperature electrical contactors, etc.
- **Profiled Rod** : A rod with a complex cross-section, such as a groove, hole or step shape, obtained by extrusion, turning or electromachining. It is suitable for special connection structures or multifunctional composite structural parts.
- **Pin-Type Rod** : Mainly used as small counterweights, positioning or conductive components in micro-precision devices, medical equipment, and electric vacuum components, usually with a diameter of <5 mm.
- **Long Rod/Large-Dimension Rod** : Used for load-bearing structures and high-energy impact components, such as supersonic armor-piercing cores, inertial test modules, etc., emphasizing high strength, high uniformity and density.

In addition, with the development of personalized manufacturing and functional integration, some tungsten alloy rods have been structurally composited with ceramics, polymers or functional coatings, making them have multiple composite functions such as heat protection, corrosion resistance, and electromagnetic shielding.

In terms of product supply, tungsten alloy rods are usually available in three types: polished rods (surface polished), lathe rods (finished), and black rods (unprocessed). The surface quality and dimensional tolerances are differentiated according to the application areas. Some precision products require Ra values <0.4 μm and dimensional accuracy of ±0.01 mm, which are widely used in high-end equipment such as medical imaging, microwave communications, and inertial instruments.

With the development of material engineering and the evolution of processing technology, the product forms of tungsten alloy rods are also constantly enriched. From traditional solid rods with equal cross-sections, to functionally gradient structural rods, multi-phase co-fired structural rods and even 3D printed porous rods, they are gradually adapting to emerging application scenarios such as extreme service environments, intelligent structural control and multi-functional integration, providing more flexible and efficient material solutions for advanced manufacturing systems.

1.2 Introduction to Heavy Tungsten Alloy (W-Ni-Fe / W-Ni-Cu) System

Tungsten Heavy Alloy (THA) is a type of pseudo alloy or metal composite system that is based on tungsten (W) and is formed by adding a certain proportion of bonding metals (such as nickel Ni, iron Fe, copper Cu, etc.). Its typical characteristics are high density, high strength, good mechanical processing performance and thermal stability at room temperature, as well as low thermal expansion coefficient and good corrosion resistance. Tungsten Heavy Alloy is widely used in technology-intensive fields such as high-performance counterweight components, radiation protection components, military armor-piercing components, inertial components, etc. It is one of the irreplaceable key structural materials in the current high-end equipment manufacturing.

Among all the high-density tungsten alloy systems, the two most representative and most industrially mature ones are:

- **Tungsten-nickel-iron alloy system (W-Ni-Fe)**
- **Tungsten-nickel-copper alloy system (W-Ni-Cu)**

The basic structure of these two systems is a "two-phase structure", that is, tungsten particles with a volume fraction of more than 90% are the main phase, and they are tightly connected by a continuous bonding phase (matrix) composed of nickel and iron or copper , thus forming an alloy structure with high density and high uniformity.

W-Ni-Fe tungsten alloy: high strength industrial main type

The W-Ni-Fe system is the type of tungsten alloy with the largest output and the most extensive application. Its typical composition is:

- **Tungsten (W)** : 90–97 wt %
- **Nickel (Ni)** : 3–7 wt %
- **Iron (Fe)** : 1–3 wt %
- **Density range** : 17.0–18.5 g/cm³

The alloy has extremely high tensile strength (generally up to 900-1200 MPa), good fracture ductility (elongation can reach 10-30%), and due to the iron content, its magnetic properties are adjustable. It is suitable for occasions requiring outstanding mechanical properties, such as inertial components, seismic counterweights, and dynamic load-resistant structural parts.

advantage :

- High strength and good wear resistance
- Heat treatable
- Applicable to military structural parts and aerospace inertial devices

shortcoming :

- The Fe content makes it magnetic, which is not suitable for weighting some electronic devices.
- The corrosion resistance is slightly lower than that of Ni-Cu system

W-Ni-Cu tungsten alloy: low magnetic properties and high conductivity

W-Ni-Cu alloy replaces iron with copper to form a non-magnetic or low-magnetic bonding phase. Its typical composition is:

- **Tungsten (W)** : 90–95 wt %
- **Nickel (Ni)** : 2–5 wt %
- **Copper (Cu)** : 2–4 wt %
- **Density range** : 17.0–18.0 g/cm³

This type of tungsten alloy has a slightly lower tensile strength (about 700-900 MPa), but has better electrical conductivity and corrosion resistance, and its magnetic permeability is close to 1. It is a typical non- magnetic structural material and is widely used in electronics, vacuum, medical diagnostic equipment and other equipment that have extremely high requirements for electromagnetic interference control.

advantage :

- Non-magnetic or weakly magnetic, suitable for precision instruments
- Thermal conductivity and electrical conductivity are better than W-Ni-Fe system
- Strong resistance to seawater corrosion, suitable for marine and medical fields

shortcoming :

- The tensile strength and toughness are slightly low, not suitable for high dynamic load structures
- Slightly higher cost and slightly more difficult to manufacture

Other developing tungsten alloy systems

tungsten alloy systems have been developed in the direction of functionalization and high-end in recent years , such as:

- **W-Ni-Co system** : used to replace iron-containing magnetic problems and enhance heat resistance
- **W-Cu system** : suitable for high heat flux devices, such as microelectronic cooling modules
- **W-Polymer structural composite rod** : A tungsten-polymer composite structure developed to solve the contradiction between weight and processability
- **Nano- tungsten alloy system : Introducing nano** - tungsten powder or intermetallic compound particles (such as TiC , LaB_6) to improve material density and strength toughness

Organizational structure characteristics and performance control points

high-density tungsten alloys are a composite dual-phase structure of "tungsten particles + binder phase", in which the volume fraction of tungsten particles exceeds 85%, playing the main load-bearing role, while the Ni-Fe or Ni-Cu binder phase determines the overall ductility and processability. Its organizational uniformity, tungsten particle size distribution, and binder phase continuity determine the ultimate mechanical properties and service life of the rod.

- **Tungsten particle distribution** : The particle size is generally between 10–50 µm . The smaller the particle size, the better the interface bonding and the higher the mechanical properties.
- **Sintering density** : Controlling porosity <0.5% helps improve strength and thermal conductivity;
- **Binder ratio** : too low will lead to high brittleness and difficulty in processing; too high will lead to reduced density and insufficient strength, generally controlled at 3-10 wt %;
- **Composition uniformity** : prevent element segregation or agglomeration and improve product consistency;
- **Microstructure control** : Liquid phase sintering and heat treatment can achieve grain refinement and uniform structure, thereby improving fatigue resistance.

Conclusion

tungsten alloy rods, W-Ni-Fe and W-Ni-Cu systems support two core application systems: **high-strength structure and low- magnetic electronics . Their flexibility in composition control, organization regulation and performance adaptation ensures the irreplaceability of tungsten alloy rods in aerospace, national defense, precision electronics, medical nuclear engineering and other fields. With technological progress, the performance boundaries and application depth of** tungsten alloy rods in the field of high-end manufacturing will be further expanded in the future through microalloying, nano-strengthening and functional composite.

1.3 Common Sizes, Shapes and Surface Conditions of Tungsten Alloy Rods

As a high-performance structural material, tungsten alloy rods present various sizes, shapes and surface conditions in different industries and usage environments. Its geometry and surface characteristics are not only related to assembly accuracy and service life, but also directly affect processing efficiency, structural stability and service reliability. Therefore, a deep understanding of the standardized and customized forms of tungsten alloy rods is the basis for product design and engineering material selection.

1. Dimensions

tungsten alloy rods is usually divided into two categories: standardized and customized according to their uses. Common specifications include diameter (or side length), length, roundness, straightness and dimensional tolerance.

- **Diameter range** : 1 mm to 200 mm, the most commonly used specifications are 3 mm to 100 mm;
- **Length range** : 10 mm ~ 2000 mm, conventionally processed bars are mostly controlled at 50 mm ~ 1000 mm;
- **Length tolerance** : generally ±0.5 mm, precision machining can reach ±0.1 mm;
- **Straightness error** : industrial-grade products are controlled within 0.5 mm/m, and precision-grade products can reach 0.1 mm/m;
- **Coaxiality and verticality control : Tungsten alloy** rods used for dynamic parts require higher geometric consistency, generally controlled within the range of ±0.02 mm.

For bars used in specific fields (such as ballistic weapons, high-speed gyroscopes, and precision optical systems), thermal expansion control and consistency of delivery dimensions must also be considered. Quality control is usually carried out in combination with CAD modeling and three-dimensional detection systems.

2. Shape Classification

The shape and structure design of tungsten alloy rods must meet the integration requirements of different mechanical components, thermal control units, electrical connections or inertial elements. The main shapes can be summarized as follows:

1. **Solid Round Rod** : The most common structure, suitable for most industrial counterweights, electrodes and inertial components.
2. **Hollow Rod** : It has the function of weight reduction or liquid cooling and is often used in the medical and aerospace fields.
3. **Square / Rectangular Rod** : Suitable for frame structures, electrical contact bases, etc.
4. **Profiled Rod** : With special designs such as slots, holes, recesses , chamfers, etc., it is mostly used for customized assembly parts and complex integrated structures.
5. **Micro Rod** : The diameter is less than 2 mm, mostly used in microwave components, nuclear medicine, precision gyroscopes or MEMS systems.
6. **Stepped / Tapered Rods** : Suitable for high inertia or power transmission occasions, meeting the needs of functional and structural integration.

3. Surface Condition

tungsten alloy rod directly affects its fatigue resistance, matching accuracy, corrosion protection effect and material service life. Common surface conditions include:

1. **As-Sintered**
   is an unprocessed surface with a layer of black oxide film, which is suitable for subsequent machining or structural parts with no exposed surface.
2. **the turned rod**
   is roughly processed, and the roughness is generally Ra 1.6-3.2 μm , which is suitable for medium-precision accessories.
3. **Ground Rods**
   are precision cylindrically ground to have excellent surface quality and dimensional consistency, with Ra less than 1.0 μm , and are widely used in medical and electronic equipment.
4. **The polished rod**
   is further treated to a mirror finish, with an Ra value of 0.2–0.4 μm . It is often used in devices with high appearance requirements, low friction or optical related devices.
5. **Coated Rod**
   uses electroplating, chemical plating or PVD to form a functional surface, such as Ni, Cr, TiN coating, to improve corrosion resistance, electrical contact or wear resistance.
6. **Special surface treatment (Electropolished / Plasma-Finished)**
   is suitable for high clean environment, high radiation occasions or medical / nuclear technology equipment to improve surface density and remove micro cracks.

4. Accuracy level

According to the processing accuracy and testing requirements, tungsten alloy rods can be divided into the following three grades:

- **Industrial Grade (Standard Grade)** : Suitable for general protection, structural support, counterweight components, dimensional tolerance ±0.5 mm;
- **Precision Grade** : Applicable to moving components, guide components and inertial systems, with tolerance controlled at ±0.1 mm, Ra < 1.6 μm ;

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- **Ultra-Precision Grade** : Used in medical, aerospace and gyroscope systems, with dimensional tolerance up to ±0.01 mm, Ra < 0.4 μm , and requires NDT testing and metallographic qualification standards.

With the increasing market demand for special-shaped structures and composite functional parts, tungsten alloy rods are increasingly showing a trend of high-end, customized and intelligent in terms of size, structure and surface processing. In the future, relying on cutting-edge manufacturing technologies such as laser processing, micro-milling, ultra-precision grinding, plasma packaging, etc., tungsten alloy rods will continue to expand their engineering potential in core applications such as complex structures, high-frequency vibrations, extreme thermal fields and precision counterweights.

1.4 Classification of Tungsten Alloy Rods (by Composition/Use/Processing Method)

Tungsten alloy rods are widely used in many key fields such as aerospace, nuclear energy, medical, military industry and high-end manufacturing. They are of various types and have different uses. In order to organize the product system more efficiently, guide material selection and process optimization, it is usually necessary to systematically classify tungsten alloy rods according to different dimensions. The three most common classification methods include: by composition, by use, and by processing method.

1. Classification by ingredients

Tungsten alloy rods are mainly composed of tungsten (W) and bonding metals (such as Ni, Fe, Cu, Co, etc.). According to the differences in alloy systems, they can be divided into:

1. **W-Ni-Fe Alloy Rod**
   - Content: W 90–97%, Ni 2–7%, Fe 1–3%
   - Features: Magnetic alloy, high strength, good ductility
   - Application: inertial components, military counterweights, high-strength structural parts
2. **W-Ni-Cu Alloy Rod**
   - Content: W 90–95%, Ni 2–5%, Cu 2–4%
   - Features: non-magnetic or low magnetic, good thermal conductivity, strong corrosion resistance
   - Application: medical equipment, nuclear medicine, electronic countermeasure components
3. **W-Cu Alloy Rod**
   - Content: W 70–90%, Cu 10–30%
   - Features: Excellent electrical and thermal conductivity, suitable for high-power devices
   - Application: electrodes, radiators, vacuum contacts, etc.
4. **Special alloy systems (such as W-Ni-Co, W-Re, W- TiC)**
   - Features: Special high temperature performance or enhanced radiation resistance

- o Application: aerospace thermal control components, nuclear materials, laser countermeasure systems

5. **Doped modified alloy**
   - o earth (Y_2O_3 , CeO_2) , carbide (TiC , ZrC) , etc.
   - o Function: Improve microstructure, increase high temperature strength or corrosion resistance

2. Classification by purpose

According to the specific usage scenarios of tungsten alloy rods, they can be divided into the following categories:

1. **Tungsten Rod for Structure**
   - o Function: load bearing, high temperature structure support, rotor parts
   - o Typical applications: satellite inertial structures, gyroscopes, engine centering axes
2. **Tungsten Rod for Protection**
   - o Function: Shielding X-rays, gamma rays, neutron radiation
   - o Applications: Medical CT, nuclear reactors, isotope transport containers
3. **Military Kinetic Tungsten Rod**
   - o Function: high-density impact, armor-piercing, kinetic energy killing
   - o Application: APFSDS core, high explosive core material, tail fin counterweight
4. **Tungsten Rods for Electronic Devices**
   - o Function: electrical and thermal conductivity, thermal diffusion, microwave absorption
   - o Application: Chip packaging, cooling structure, electrode electrical contact
5. **Tungsten Rods for Medical Devices**
   - o Function: radiotherapy needle, tumor intensity modulation component, micro counterweight
   - o Requirements: non-magnetic, ultra-clean, high density
6. **Tungsten rod for scientific research**
   - o Applications: particle accelerators, neutron source targets, vacuum anodes, experimental instruments

3. Classification by processing method

tungsten alloy rods vary depending on the manufacturing process. Common processing methods include:

1. **Powder Metallurgy Pressed Rods (CIP / Molded)**
   - o Process: Cold isostatic pressing, uniaxial pressing followed by high temperature sintering
   - o Features: dense organization, batch molding
2. **Hot Isostatic Pressed Rod (HIP Rod)**
   - o Process: After encapsulation, the whole is densified under high temperature and high pressure

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  - Advantages: Ultra-high density, extremely low porosity, suitable for high reliability requirements
3. **Extruded rods**
  - Process: Tungsten alloy is expected to be hot extruded into long strips
  - Application: Microwave communication, thermal control components
4. **Turning Rods/ Grinding Rods**
  - Process: High-precision finished rods are obtained through machining
  - Features: Ra < 1 μm , ±0.01 mm dimensional tolerance
5. **Injection molded rods (MIM process)**
  - Features: Suitable for small and complex structure bars
  - Application: Medical tungsten parts, micro inertial systems
6. **Sintered blank rod (black skin rod)**
  - Status: Unprocessed or only preliminarily cut, suitable for subsequent customized processing
7. **3D Printed Tungsten Rods (Additive Manufacturing)**
  - Status: Still in the exploratory stage, suitable for small batch products with complex structures and flexible requirements

Summarize

As a functional structural material, the classification of tungsten alloy rods is not only the basis for product standardization and serialization, but also has important guiding significance for performance design, process selection and market promotion. The material system can be clarified by composition, the function can be accurately positioned by purpose, and the best balance between quality and efficiency can be achieved by process. In the future, as high-end manufacturing develops towards intelligence and customization, the multi-dimensional classification system of tungsten alloy rods will become more refined and tend to be digitalized and modularized, providing more scientific and systematic support for material research and development and industrial applications.

1.5 Comparison between tungsten alloy rod and tungsten copper rod , tungsten rod and other materials

Tungsten alloy rod, tungsten copper rod and pure tungsten rod are several commonly used tungsten-based materials in industry . Due to their different physical properties and application fields, they play an important role in the manufacturing and electronics industries. Understanding their differences will help you make reasonable choices when designing and selecting materials.

1.5.1 Comparison of composition and basic properties

Material Type	Main Ingredients	Density (g/cm³)	hardness	Thermal conductivity	Conductivity	Mechanical strength	Main Features

Tungsten Alloy Rod	Tungsten + alloy elements such as nickel, iron or copper	17.0 ~ 18.5	Higher	medium	Low to medium	excellent	High density, high strength, mechanical properties are better than pure tungsten rod
Tungsten Copper Rod	Tungsten + Copper	14.0 ~ 16.0	medium	Very high	Higher	better	Combining the high density of tungsten with the good electrical and thermal conductivity of copper , it provides excellent thermal management performance
Pure tungsten rod	Tungsten	19.3	Very high	Low	Low	Brittle	Highest density, high temperature resistance, high hardness, but relatively brittle

1.5.2 Density and weight

- **Tungsten rods** have the highest tungsten content and the largest density (19.3 g/cm³), so they are suitable for applications with extremely high requirements on weight and density, such as counterweights, radiation shielding, etc.
- **Tungsten alloy rods** have a slightly lower density, but are still high-density materials, and their strength is better than pure tungsten, making them suitable for manufacturing high-strength and high-density parts.
- **Tungsten copper rod** has a lower density than tungsten and tungsten alloys because it is doped with copper, but copper has excellent thermal conductivity, making it more popular in situations where thermal management is required.

1.5.3 Thermal and electrical conductivity

- **Tungsten copper rods** have a higher copper content and their thermal and electrical conductivity are significantly better than tungsten alloy rods and pure tungsten rods. Therefore, they are widely used in electronic radiators, electrodes and vacuum electronic devices.
- **tungsten alloy rods** is average, and the electrical conductivity is lower than tungsten copper, but better than pure tungsten, which is suitable for mechanical structures and high-temperature components.

- **Pure tungsten rods have relatively low** thermal and electrical conductivity and are more commonly used in environments requiring high temperature resistance and high density.

1.5.4 Mechanical properties and processability

- **Tungsten alloy rods** have significantly improved toughness and mechanical strength due to the addition of alloying elements. Their processing performance is better than that of pure tungsten and they are suitable for processing complex parts.
- **Tungsten copper rod** combines the strength of tungsten and the ductility of copper , with good toughness and thermal fatigue resistance, but the copper content limits its high temperature performance.
- **Pure tungsten rods** have high hardness and brittleness, are difficult to process, and are prone to cracking. They are mostly used in high-temperature environments and structural parts.

1.5.5 Typical application areas

Material	Application Examples
Tungsten Alloy Rod	Weight counterweight, high-strength structural parts, armor-piercing cores, aerospace parts
Tungsten Copper Rod	Electrodes, radiators, vacuum tube components, microwave devices
Pure tungsten rod	High temperature furnace parts, filaments, radiation shielding, nuclear industry materials

Summarize

Tungsten alloy rods, tungsten copper rods and pure tungsten rods each have their own advantages. Tungsten alloy rods are widely used in the field of mechanical structures due to their high density and mechanical strength; tungsten copper rods have become an indispensable material in the electronics industry due to their excellent thermal and electrical conductivity; pure tungsten rods are suitable for special high temperature and radiation environments due to their extremely high density and high temperature resistance. Reasonable selection of materials requires comprehensive consideration of factors such as density, strength, thermal conductivity and application environment.

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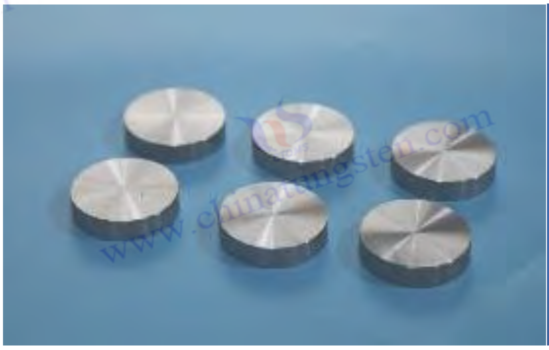
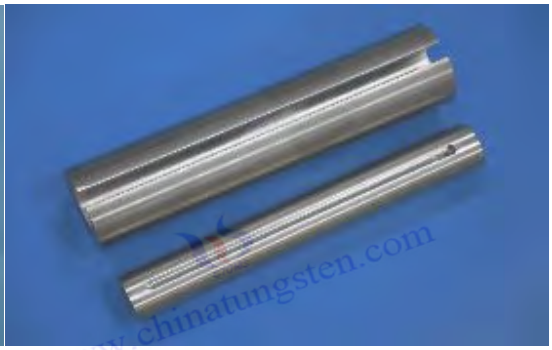

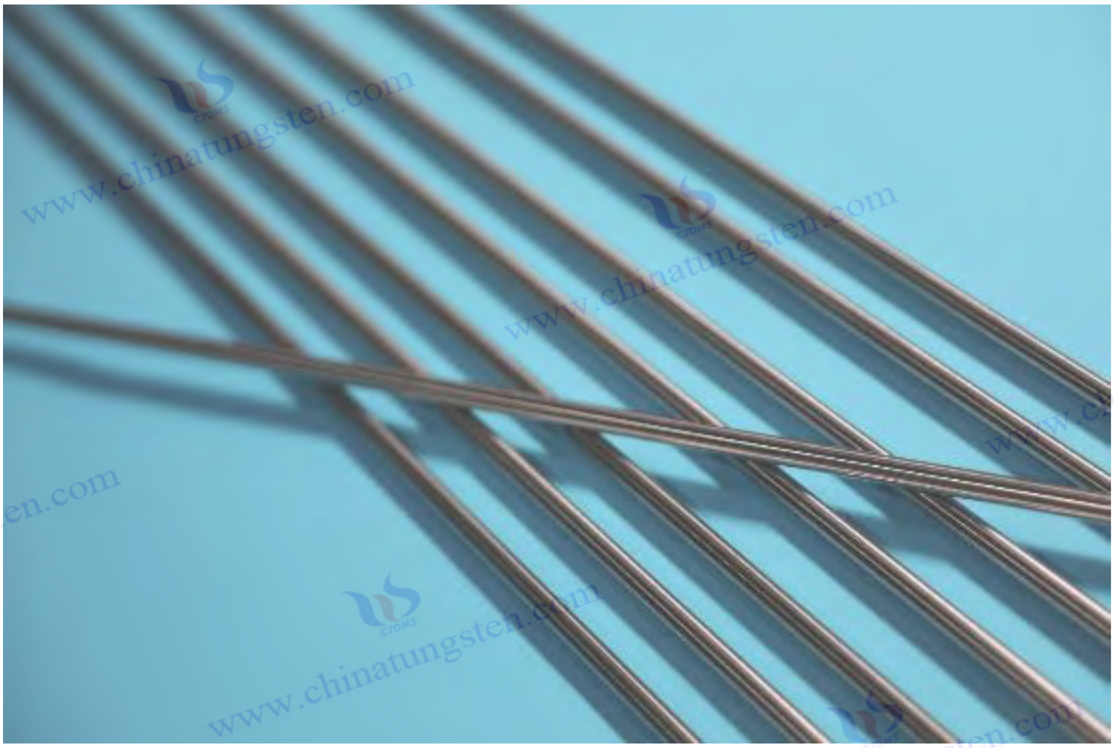

Chapter 2 Physical and Mechanical Properties of Tungsten Alloy Rods

2.1 Density, specific gravity and dimensional accuracy control

As a high-density material, the control of density and size of tungsten alloy rods is directly related to their performance and the quality requirements of subsequent applications. Accurate density and size control is the key to ensuring the stability and consistency of tungsten alloy rod products .

2.1.1 Density and specific gravity

- **Density** is the mass of a material per unit volume and is the core indicator for measuring the quality of tungsten alloy rod materials . The density of tungsten alloy rods is usually between 17.0 and 18.5 g/cm³, and the specific value depends on the tungsten content and the proportion of alloying elements.
- **Specific gravity** is the ratio of the material density to the density of water. Since the density of water is 1 g/cm³, the specific gravity value of tungsten alloy rod is basically equal to its density value.

Accurate control of density can ensure that the material achieves the expected physical properties, such as precise weight distribution requirements, mechanical strength and electromagnetic shielding effect.
Too large density deviation will cause fluctuations in product performance, and in serious cases it will affect the assembly and fit of parts and the safety of the final product.

2.1.2 Key factors of density control

- **Ratio of raw material components** : The higher the tungsten content, the greater the density. Reasonable ratio of tungsten and alloy elements (such as nickel, iron, copper) is the basis for controlling density.
- **Sintering process parameters** : temperature, time and atmosphere control have a significant impact on density . Too low sintering temperature will easily lead to increased porosity and reduced density; too high sintering temperature may cause over-burning and reduced material performance.
- **Powder particle size and uniformity** : Fine powder and uniform mixing help to improve density, reduce porosity and increase material density.
- **Cold working and heat treatment** : Appropriate forging, extrusion and heat treatment processes can further eliminate internal porosity in the material and improve density.

2.1.3 Dimensional accuracy control

tungsten alloy rod refers to the deviation range between its length, diameter and external dimensions and the design value. High-precision dimensional control ensures the stability and reliability of tungsten alloy rods during machining, assembly and use.

- **The dimensional tolerance** is usually determined according to customer requirements and standards. Generally, the diameter tolerance can be controlled within the range of ±0.01 mm to ±0.05 mm.
- **Surface roughness** is also a part of dimensional accuracy. Good surface condition can reduce the difficulty of machining and improve part performance.
- Advanced processing equipment and measuring instruments (such as three-coordinate measuring machines and laser diameter gauges) are used to ensure high dimensional accuracy and consistency.

2.1.4 Technical measures for dimensional accuracy control

- **CNC processing equipment** : Use high-precision CNC lathes and grinders for processing to ensure stable dimensional accuracy.
- **Online detection and feedback control** : An automatic measurement system is used during the production process to monitor dimensional deviations in real time and make adjustments.
- **Heat treatment process optimization** : control deformation during heat treatment to avoid dimensional loss of control.
- **Strict process specifications** : including cutting, grinding, polishing and other processes to ensure that each step of processing meets the dimensional requirements.

summary

tungsten alloy rods is the basis for ensuring their high performance. The accuracy of density directly affects the mechanical properties and application effects of the material. Strict control of dimensional accuracy guarantees the processing performance of the product and the reliability of the final assembly. By optimizing the raw material ratio, process parameters and advanced processing and testing technology, it can effectively ensure that the physical and mechanical properties of tungsten alloy rods meet the design requirements.

2.2 Tensile strength, yield strength and elongation

tungsten alloy rods are important indicators of their ability to withstand loads in practical applications, among which tensile strength, yield strength and elongation are key parameters for evaluating material strength and plasticity. Understanding and controlling these performance parameters will help ensure the safety and reliability of tungsten alloy rods during manufacturing and use.

2.2.1 Tensile Strength

Tensile strength refers to the maximum stress that a material can withstand in a tensile test, reflecting the material's ability to resist fracture. The tensile strength of tungsten alloy rods is usually high, typically ranging from 600 to 1200 MPa, and the specific value is affected by the alloy composition, manufacturing process, and heat treatment status.

- High tungsten content generally increases the tensile strength of the material, but too high a tungsten ratio may result in reduced toughness.
- Through reasonable alloy design and heat treatment process, the plasticity and toughness of the material can be improved while ensuring high strength.
- Tungsten alloy rods with high tensile strength are suitable for mechanical parts and structural parts that bear large tensile loads.

2.2.2 Yield Strength

Yield strength is the stress value at which a material begins to undergo permanent plastic deformation when subjected to stress, reflecting the elastic-plastic limit of the material. The yield strength of tungsten alloy rods is usually slightly lower than the tensile strength, generally ranging from 400 to 900 MPa.

- The yield strength affects the safety margin of the material in practical applications.
- For tungsten alloy rods, higher yield strength means that they can withstand greater working stress during use without permanent deformation.
- The yield strength can be effectively improved by optimizing the sintering temperature and subsequent thermomechanical treatment.

2.2.3 Elongation

Elongation is the ability of a material to deform plastically before breaking, usually expressed as a percentage, and is a key indicator for measuring the toughness and plasticity of a material. The elongation of tungsten alloy rods is generally low, typically ranging from 1% to 10%.

- A low elongation indicates that the material is brittle and prone to breakage; a high elongation indicates that the material has good plastic deformation ability.
- Alloy elements such as nickel and iron added to tungsten alloy help to increase the elongation and make the material less prone to brittle cracking.
- The increase in elongation is beneficial to the forming and safe use of tungsten alloy rods under complex working conditions.

2.2.4 Factors affecting mechanical performance

- **Composition ratio** : The higher the tungsten content, the higher the strength, but the elongation may decrease; the addition of alloying elements such as nickel and iron can improve toughness.
- **Sintering process** : Sintering temperature, time and atmosphere directly affect the microstructure and density of the material, thereby affecting the strength and plasticity.
- **Heat treatment and machining** : Appropriate heat treatment such as annealing, aging, and machining processes (forging, extrusion) can adjust the internal structure of the material and improve the mechanical properties.
- **Grain size** : A fine and uniform grain structure contributes to improved strength and toughness.

summary

The tensile strength, yield strength and elongation of tungsten alloy rods are important indicators to measure their comprehensive mechanical properties. By optimizing the composition design and process control, tungsten alloy rods can obtain appropriate plasticity while ensuring high strength to meet the material performance requirements of different industrial applications. Mastering and controlling these performance parameters is crucial for the quality assurance and application development of tungsten alloy rods.

2.3 Hardness and impact resistance

The hardness and impact resistance of tungsten alloy rods are important indicators for evaluating their wear resistance and damage resistance, and play a key role in ensuring the stability and service life of materials under complex working conditions. Reasonable control of hardness and impact resistance is an important means to achieve balanced performance of tungsten alloy rods.

2.3.1 Hardness

Hardness reflects the ability of a material to resist local plastic deformation and wear, and is usually measured using methods such as Brinell hardness (HB), Rockwell hardness (HRC) or Vickers hardness (HV).

- tungsten alloy rods is generally in the range of **200~400 HB** , and the specific value varies according to the tungsten content and the type and proportion of alloying elements.
- High tungsten content usually corresponds to higher hardness, and the addition of alloying elements such as nickel and iron can adjust the balance between hardness and toughness.
- Tungsten alloys with higher hardness are suitable for manufacturing wear-resistant parts and scratch-resistant components.
- The hardness can be further increased by heat treatment (such as aging treatment).

2.3.2 Impact Toughness

Impact resistance is the ability of a material to resist sudden external force without breaking, and is usually evaluated by the Charpy Impact Test or the Izod impact test.

- Tungsten alloy rods generally have moderate to good impact resistance, with typical impact absorption energy ranging from **5 to 20 J/cm²** .
- Impact resistance is significantly affected by the material 's grain structure, alloying elements and heat treatment process.
- Adding elements such as nickel and iron to the alloy can significantly improve the material's toughness and impact resistance and reduce the risk of brittle fracture.
- Optimized thermomechanical processing (e.g. forging, extrusion) can also help improve impact resistance.

2.3.3 Balance between hardness and impact resistance

tungsten alloy rods usually requires finding the best balance between hardness and impact resistance:

- Although too high a hardness improves wear resistance, it may cause the material to become brittle and reduce its impact resistance.
- Appropriate hardness combined with good toughness can ensure that the material is both wear-resistant and not easy to break under high-intensity use environments.
- tungsten alloy rods, such as alloy composition design, sintering parameter control, and optimization of heat treatment and cold working procedures, are the key to achieving performance balance.

summary

Hardness and impact resistance are two important aspects of the physical and mechanical properties of tungsten alloy rods. Through appropriate material ratio and process control, tungsten alloy rods with both high hardness and good impact resistance can be obtained to meet the requirements of different industrial fields for material wear resistance and damage resistance. Reasonable performance balance can improve the application reliability and service life of tungsten alloy rods.

2.4 Thermal conductivity, thermal expansion coefficient and high temperature performance

Tungsten alloy rods are widely used in many industrial fields, especially in high temperature and heat load environments. Their thermal conductivity, thermal expansion coefficient and high temperature performance directly affect the stability and service life of the material. Understanding and optimizing these thermophysical properties is the key to designing high-performance tungsten alloy products.

2.4.1 Thermal Conductivity

Thermal conductivity is the ability of a material to transfer heat. The thermal conductivity of tungsten alloy is between pure tungsten and other alloy materials, usually in the range of **70 ~ 120 W/(m·K)** .

- Tungsten itself has excellent thermal conductivity (about 170 W/(m·K)), but adding alloying elements such as nickel and iron will reduce the overall thermal conductivity.
- tungsten alloy meets many applications that require rapid heat dissipation, such as electronic radiators, high-temperature tooling and heat exchange equipment.
- The density and grain structure of the material have a significant impact on thermal conductivity, and the sintering and heat treatment processes need to be controlled to improve density and optimize thermal conductivity.

2.4.2 Coefficient of Thermal Expansion (CTE)

The coefficient of thermal expansion indicates the ability of a material to expand in size as the temperature changes. The coefficient of thermal expansion of tungsten alloy is relatively low, about **$4.5 \times 10^{-6} \sim 6.5 \times 10^{-6}$ K^{-1}** .

- The low thermal expansion coefficient makes tungsten alloy have small dimensional changes and low thermal stress in high temperature environments, making it suitable for use in precision equipment and high-temperature structural parts.
- The addition of alloying elements will slightly increase the coefficient of thermal expansion, but it is still much lower than many commonly used metal materials (such as copper and aluminum).
- The stability of the thermal expansion coefficient is very important for preventing thermal fatigue cracks during welding, assembly and use.

2.4.3 High-Temperature Performance

Tungsten alloy rods have excellent high temperature properties, including high melting point, good high temperature strength and thermal fatigue resistance.

- The melting point of tungsten is as high as 3422℃. Although the melting point of tungsten alloy is slightly lower, it can still maintain good mechanical properties in an environment above 1500℃.
- Its oxidation resistance at high temperature is slightly worse than that of pure tungsten , and it needs to be coated on the surface or used in a protective atmosphere to prevent oxidation damage.

- tungsten alloy make it widely used in aerospace, military industry and high temperature furnace manufacturing.
- Thermal fatigue performance determines the life of the material in repeated heating and cooling cycles. Optimizing the material composition and microstructure can improve the thermal fatigue resistance.

summary

Tungsten alloy rods have good thermal conductivity and low and stable thermal expansion coefficient, which makes them perform well in high temperature environments. Their high temperature strength and thermal fatigue performance provide reliable guarantees for their application in extreme working conditions. Through reasonable material design and process optimization, the thermophysical properties of tungsten alloy rods can be further improved to meet the needs of more high-end fields.

2.5 Electrical properties, magnetic response and radiation resistance

Tungsten alloy rods have important applications in certain special fields such as electronic devices, magnetic shielding and nuclear industry. Their electrical properties, magnetic response and radiation resistance are key indicators for evaluating the applicability of materials. Mastering these properties will help optimize material design and expand its application range.

2.5.1 Electrical Properties

tungsten alloy is significantly affected by the alloy composition and is usually lower than pure tungsten but higher than other heavy metal alloys.

- The electrical conductivity of pure tungsten is relatively high, about 18×10^{6} S/m, but the electrical conductivity of tungsten alloy generally drops to $5\sim12 \times 10^{6}$ S/m due to the presence of alloying elements such as nickel and iron.
- The resistivity of tungsten alloy is higher than that of pure tungsten, and it is suitable for applications that require a certain resistance but also high strength, such as resistor elements, electrode materials, etc.
- Optimizing the composition ratio and heat treatment process can improve the electrical properties and achieve a balance between strength and conductivity.

2.5.2 Magnetic Response

Tungsten itself is a paramagnetic material. The magnetic properties of tungsten alloys mainly depend on the type and content of alloying elements.

- Adding iron group elements (such as iron and nickel) will enhance the magnetic response of the alloy, which may exhibit certain ferromagnetism or paramagnetism.
- tungsten alloy have an impact on its stability in magnetic shielding materials and magnetic field environments.

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- In some applications, tungsten alloys with low magnetic response are preferred to avoid magnetic field interference.

2.5.3 Radiation Resistance

Tungsten and tungsten alloys are widely used in the nuclear industry and radiation protection due to their high atomic number and density, and have good radiation resistance.

- Tungsten alloy has excellent shielding effect on electromagnetic radiation such as neutrons and gamma rays, and is often used in nuclear reactor protection materials and radioactive equipment protective covers.
- The addition of alloying elements generally does not significantly reduce the radiation resistance, but attention should be paid to the uniformity and density of the alloy to prevent radiation penetration.
- Tungsten alloy exhibits good structural stability and resistance to radiation damage in irradiated environments and is suitable for long-term use.

summary

tungsten alloy rods lay the foundation for their application in the fields of electronics, magnetic shielding and nuclear industry. By adjusting the alloy composition and process parameters, the performance can be optimized and customized to meet the needs of different industrial environments and enhance the comprehensive use value of the material.

2.6 Corrosion resistance and chemical stability analysis

Tungsten alloy rods are exposed to chemical media and humid air in a variety of industrial environments. Their corrosion resistance and chemical stability are key properties to ensure long-term reliable use of the material. In-depth analysis of the corrosion resistance of tungsten alloys can help guide material selection and protection measures design.

2.6.1 Corrosion Resistance

Tungsten alloy has good corrosion resistance, mainly manifested in:

- **It has strong tolerance to most acid and alkali media** , especially excellent performance in neutral or weak acid environments, and is suitable for chemical equipment and instrument components.
- **A stable oxide film is formed on the surface of tungsten** , which can effectively isolate the corrosive medium and delay further corrosion of the material.
- In strong oxidizing acid (such as nitric acid, perchloric acid), the corrosion resistance of tungsten alloy may be challenged and protective measures need to be taken.
- The content and distribution of alloying elements (such as nickel and iron) affect the overall corrosion resistance of tungsten alloy. Uniform alloy structure helps to improve corrosion uniformity and corrosion resistance.

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2.6.2 Chemical Stability

tungsten alloy is reflected in the fact that the chemical properties of the material are not easily changed in various environments. The main features include:

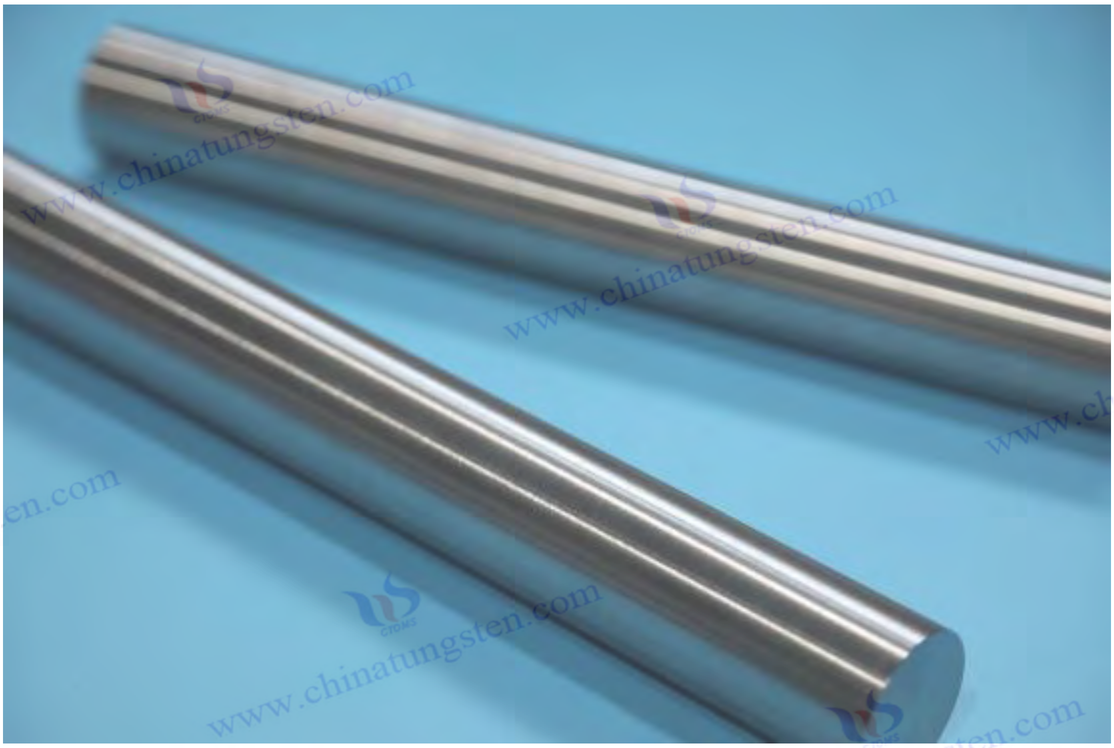
- **The high melting point and thermal stability** make tungsten alloy stable in high temperature and harsh environment, and not easy to decompose or deform.
- It shows good stability to most common chemical media such as water and alkali solution.
- In air and at room temperature, the oxide film on the surface of tungsten alloy can prevent further oxidation and enhance the durability of the material.
- When used in extreme environments such as strong acids or alkalis, a material protection layer or special process is required to improve stability.

2.6.3 Factors affecting corrosion resistance and chemical stability

- **Alloy composition and microstructure** : The type and distribution of alloying elements affect the formation and stability of the oxide film and thus the corrosion behavior.
- **Surface treatment** : Polishing, spraying or coating treatment can effectively improve the corrosion resistance of the material.
- **Environmental conditions** : temperature, medium concentration, pH value, etc. directly affect the corrosion rate and material life.
- **Manufacturing process** : High density and uniform microstructure help reduce corrosion points and extend service life.

summary

Tungsten alloy rods have excellent corrosion resistance and chemical stability, and are suitable for use in a variety of harsh environments. By rationally designing alloy composition, optimizing manufacturing processes, and adopting surface protection measures, the corrosion resistance and service life of tungsten alloy rods can be further improved to meet the needs of different industrial fields.



Chapter 3 Preparation and Forming Technology of Tungsten Alloy Rod

3.1 Raw material preparation and powder characteristics

tungsten alloy rods are highly dependent on the purity, particle size distribution, morphology and mixing uniformity of the raw materials used. High-quality raw material preparation and powder property control are the basis for achieving excellent physical and mechanical properties and stability of tungsten alloy rods. This section will introduce in detail the selection of raw materials, pretreatment, powder preparation and the influence of their properties on subsequent processes and product performance during the preparation of tungsten alloy rods.

3.1.1 Sources and types of tungsten powder

Tungsten powder is the core raw material for the production of tungsten alloy rods . Commonly used tungsten powders include:

- **Chemically reduced tungsten powder** : obtained by reducing tungstate in hydrogen, with high purity and good particle morphology, suitable for the preparation of high-performance tungsten alloys.
- **Carbothermal reduction tungsten powder** : prepared by carbothermal reduction method, with low cost, but relatively high impurity content and wide particle size distribution.
- **Spray dried tungsten powder** : used to produce high quality tungsten powder with uniform particles and regular particle morphology, which is convenient for subsequent pressing and sintering.

- **Spherical tungsten powder** : prepared by plasma spheroidization and other technologies, with good fluidity and bulk density, suitable for powder metallurgy high-performance tungsten alloy.

When selecting tungsten powder, purity, particle size, morphology and price factors must be considered comprehensively to meet specific process requirements and performance standards.

3.1.2 Selection of alloying element powder

Tungsten alloys are usually doped with alloying elements such as nickel, iron, and copper, which are mixed with tungsten powder in powder form. The particle size and morphology of the alloy powder have a great influence on the mixing uniformity and the final material properties.

- **Nickel powder** : Spherical nickel powder is commonly used with uniform particle size, which is beneficial to improving mixing uniformity and sintering density.
- **Iron powder** : Use iron powder with high purity and low oxygen content to prevent impurities from affecting material properties.
- **Copper powder** : Spherical or flake copper powder is commonly used. Good thermal conductivity is particularly important for the preparation of tungsten copper alloy .

The alloy element powder should maintain uniform particle distribution and avoid agglomeration to ensure the uniformity of the alloy composition on a microscopic scale.

3.1.3 Powder pretreatment process

Powder pretreatment is crucial to improving particle performance and mixing effects. Common pretreatment methods include:

- **Drying treatment** : remove moisture adsorbed on the powder surface to prevent pores from forming during the sintering process.
- **Screening and grading** : Powders of different particle sizes are separated by sieves to obtain mixed powders with uniform particle size distribution and improve pressing density.
- **Surface activation** : Mechanically or chemically activate the powder to improve the bonding force between particles and promote sintering density.
- **Mixing and homogenization** : Use ball mills, mixers and other equipment to mix evenly for a long time to ensure uniform distribution of alloy elements and avoid uneven performance.

3.1.4 Particle size distribution and morphology of powders

The particle size distribution has an important influence on the density, mechanical properties and processing performance of tungsten alloy rods:

- **Fine powder** is beneficial to improving sintering density and mechanical properties, but too fine powder is easy to agglomerate, affecting fluidity and processing performance.
- **Coarse powder** has good fluidity, but has large porosity and poor density during sintering.

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- **The ideal particle size distribution** is usually a broad spectrum distribution, that is, the fine powder fills the gaps between the coarse powders to obtain a high density.

Appearance:

- **Spherical powder** has good fluidity and bulk density, which is conducive to the pressing and sintering process.
- **Irregular powders** are prone to form voids between powders, but sometimes they help to improve the mechanical locking strength .

3.1.5 Powder mixing and proportion control

tungsten alloys is highly dependent on the accurate ratio and uniform mixing of tungsten and alloying elements. In typical tungsten alloys such as W-Ni-Fe system, the tungsten content is usually above 90%, and the proportion of alloying elements is relatively low.

- High-precision weighing equipment is used to ensure the accuracy of ingredients.
- Use efficient homogenizing mixing equipment (such as ball mill, drum mixer) for thorough mixing. The time and speed need to be optimized to prevent powder agglomeration or morphology change.
- During the mixing process, an appropriate amount of lubricant (such as polyvinyl alcohol, paraffin) can be added to improve powder fluidity and compression performance.

3.1.6 Powder fluidity and bulk density

- **Fluidity** affects the uniformity and forming efficiency of powder pressing. Powder with poor fluidity can easily cause uneven pressing density, affecting the subsequent sintering quality.
- **The bulk density** determines the powder loading amount and pressing density during pressing, and is a key factor in improving the density and mechanical properties of the material.
- Fluidity and bulk density are usually adjusted and controlled by powder morphology, particle size distribution, and pretreatment process.

3.1.7 Chemical purity and impurity control of powders

- Impurity elements such as oxygen, carbon, nitrogen, sulfur, etc. will significantly affect the mechanical properties and corrosion resistance of tungsten alloy.
- Use high-purity raw materials and a clean production environment to strictly control the chemical purity of the powder.
- Use vacuum or protective atmosphere processing to reduce oxidation and impurity adsorption.

summary

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Raw material preparation and optimization of powder properties are the basis for high-performance manufacturing of tungsten alloy rods. By rationally selecting high-purity, appropriate particle size and good morphology tungsten powder and alloy element powder, combined with scientific pretreatment and mixing processes, the density and mechanical properties of tungsten alloy can be effectively improved, laying a solid foundation for subsequent forming, sintering and heat treatment processes. High-quality powder system is the key to ensure the stable performance and excellent quality of tungsten alloy rods .

3.2 Powder metallurgy pressing process (molding, isostatic pressing)

tungsten alloy rods is powder metallurgy pressing technology. By forming the uniformly mixed tungsten alloy powder under a certain pressure, a green body with a preliminary shape and density is obtained, which provides a basis for subsequent sintering and heat treatment. The selection of pressing process and parameter control directly affect the density, uniformity and subsequent performance of the green body, and are an important part of the tungsten alloy rod preparation process.

3.2.1 Basic principles of powder pressing

Powder metallurgy pressing is to use mechanical pressure to make powder particles contact and interlock with each other, reduce the porosity, and form a green billet with a certain mechanical strength. This process is mainly achieved through the rearrangement, plastic deformation and compaction of powder particles.

- **Rearrangement stage** : Powder particles move and rearrange through compression, reducing the gaps between powders.
- **Plastic deformation stage** : The particles are compressed and deformed plastically, further filling the voids.
- **Compaction stage** : reaches maximum density and forms a solid body.

The morphology, particle size distribution and fluidity of the powder have a significant impact on the pressing effect.

3.2.2 Uniaxial Pressing

Compression molding is the most commonly used pressing method in the preparation of tungsten alloy rods. The powder is pressed into the mold using uniaxial pressure to form the desired blank.

Process characteristics:

- **The equipment has simple structure** and convenient operation and is suitable for mass production.
- **The forming pressure is high, generally reaching 200~600 MPa** , which effectively increases the powder density.
- **The mold design is flexible** and can meet various cross-sectional shape and size requirements.

- **The force is unidirectional, the density distribution is uneven** , and the density at the center of the green body is lower than that on the surface, which may cause deformation during subsequent sintering.

Main process parameters:

- **Pressing pressure** : The higher the pressure, the higher the density, but too high pressure may cause die wear or powder breakage.
- **Pressing speed** : Controlling the appropriate speed can reduce powder particle breakage and improve density uniformity.
- **Holding time** : Appropriate holding time can make the powder particles fully contact and improve the strength of the green body.
- **Mold temperature** : Properly heating the mold can help improve powder plasticity and reduce cracks and deformation.

application:

Compression molding is suitable for producing tungsten alloy rods with larger size and simple cross-section. It can also be used to preform billets for subsequent secondary processing.

3.2.3 Isostatic Pressing

Isostatic pressing is a forming method that achieves high density and uniform density distribution by applying uniform multi-directional pressure to the powder body in a hydraulic or pneumatic medium.

Process characteristics:

- **The pressure is evenly transmitted and the density is evenly distributed** , effectively avoiding the density gradient problem during the molding process.
- **The pressure direction is diverse, the blank size and shape are flexible** , and it is suitable for complex shapes and high-precision tungsten alloy parts.
- **The equipment investment is high, the process is relatively complicated** , and the production efficiency is lower than that of molding.
- **It is generally divided into two categories: cold isostatic pressing (CIP) and hot isostatic pressing (HIP)** .

Main process parameters:

- **Pressure range** : Cold isostatic pressing is generally 100~400 MPa, and hot isostatic pressing can reach a high temperature and high pressure environment of more than 100 MPa.
- **Medium selection** : Liquid (such as water, oil) or gas (such as nitrogen) is often used as the pressure transmission medium.
- **Holding time** : ensure that the powder is fully compacted and deformed.

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- **Temperature Control** : Hot isostatic pressing combined with high temperatures promotes powder sintering, improving density and performance.

application:
Isostatic pressing is suitable for the preparation of high-performance tungsten alloy rods, especially key components that require uniform density and stable mechanical properties, such as alloy rods for aerospace military industry and high-end medical equipment.

3.2.4 Comparison of advantages and disadvantages between molding and isostatic pressing

project	Compression Molding	Isostatic Pressing
Equipment investment	Lower	Higher
Pressing speed	Fast, suitable for mass production	Slow, relatively low production efficiency
Density uniformity	The density gradient is obvious, and the density in the center is lower	Uniform density and few defects
Forming complexity	Suitable for simple cross-sections	Suitable for complex shapes
Finished product mechanical properties	Stable, dependent on subsequent process control	High density, high performance
cost	Low	high

3.2.5 Key technologies and process optimization

- **Mold design optimization** : Use multi-stage pressing or progressive pressing technology to reduce density gradient and improve green body uniformity.
- **Powder pretreatment** : Improve powder fluidity and lubrication properties to avoid powder particle agglomeration or mold scratches during pressing.
- **Adjustment of pressing process parameters** : Reasonably control pressure, speed and holding time to prevent powder breakage and residual stress.
- **Isostatic pressing equipment upgrade** : Adopt high pressure and high temperature integrated equipment to achieve isostatic pressing (HIP) and further improve the green body density and mechanical properties.
- **Combination of multiple processes** : Combination of compression molding and isostatic pressing to improve production efficiency and product performance.

3.2.6 Green suppression and environmental protection requirements

Modern tungsten alloy production emphasizes environmental protection and safety, and the powder metallurgy pressing process must also comply with relevant environmental protection standards:

- Dust recovery and treatment to avoid environmental pollution and health risks to operators.
- Use harmless or low-toxic lubricants to reduce process waste pollution.

- Manage energy consumption in the production process and improve energy utilization efficiency.

summary
Powder metallurgy pressing process is the key step in the forming of tungsten alloy rods. Compression molding and isostatic pressing each have their own advantages to meet different product requirements. Reasonable selection and optimization of pressing process parameters not only ensure the density and uniformity of the blank, but also provide a solid foundation for subsequent sintering and heat treatment. With technological progress, the combination of isostatic pressing and compression molding and the development of new green processes will promote the preparation technology of tungsten alloy rods to move towards high efficiency, high quality and environmental protection.

3.3 Sintering technology and atmosphere control

Sintering is a critical process in the preparation of tungsten alloy rods. It is a process that allows the powder particles to diffuse and combine through high temperature heating, thereby achieving powder densification and improving mechanical properties. Reasonable sintering technology and atmosphere control not only affect the density, structure and performance of the material, but also the dimensional stability and quality consistency of the finished product.

3.3.1 Basic principles and processes of sintering

Sintering is the process of heating the powder body to the solid diffusion temperature range of the powder material (usually 70%~90% of the melting point of the material) to allow diffusion and bonding between particles to achieve densification. The main mechanisms include:

- **Solid-state diffusion** : Tungsten and alloy element atoms diffuse at the particle interface to form grain boundary bonding.
- **Particle surface energy reduction** : Reduction of system energy through interfacial diffusion, driving pore closure and densification.
- **Grain growth** : Appropriate grain growth is beneficial to the improvement of mechanical properties, but excessive growth will lead to performance degradation.

The sintering process is usually divided into three stages: preheating, insulation and cooling. The temperature curve and insulation time need to be precisely controlled.

3.3.2 Common sintering technologies

3.3.2.1 Atmosphere protection sintering

Sintering is carried out in a protective atmosphere (such as hydrogen, argon or mixed gas) to prevent the tungsten alloy from oxidation and promote the diffusion and uniformity of alloy elements.

- Hydrogen atmosphere can effectively reduce surface oxides and improve sintering density.

- An argon inert atmosphere is suitable for avoiding the adverse effects of reducing gases on certain alloying elements.
- The atmosphere purity requirement is high, and the content of impurity gases (oxygen, nitrogen, water vapor) is lower than the ppm level.

3.3.2.2 Vacuum sintering

The high vacuum environment reduces oxidation and improves the purity and mechanical properties of the material. Vacuum sintering is suitable for the preparation of high-end tungsten alloy products.

- The vacuum degree usually reaches 10^{-3} ~10^{-5} Pa.
- Effectively prevent the introduction of impurity gases during sintering and reduce pores and impurity inclusions.
- Equipment investment and operating costs are high.

3.3.2.3 Hot Isostatic Pressing (HIP)

Combining high temperature sintering and high pressure isostatic pressing technology, ultra-high densification of tungsten alloy powder can be achieved.

- High temperature and isotropic high pressure are applied simultaneously to promote closed-cell sintering and pore elimination of the powder.
- Greatly improve the density and mechanical properties of the material, suitable for the manufacture of key components.
- The equipment is complex and costly, and is suitable for high value-added products.

3.3.3 Sintering process parameter control

- **Sintering temperature** : generally controlled at 1450°C~1600°C. If the temperature is too low, the density will be insufficient, and if the temperature is too high, it may cause coarse grains and component segregation.
- **Insulation time** : depends on the material composition and the size of the blank , generally 1 to 4 hours to ensure sufficient diffusion and densification.
- **Heating rate** : Reasonably control the heating rate to prevent excessive thermal stress in the blank and avoid cracks.
- **Cooling rate** : Moderately slow cooling to reduce thermal stress and structural deformation.

3.3.4 Effect and control technology of sintering atmosphere

Sintering atmosphere plays a decisive role in the microstructure and properties of tungsten alloy rods.

- **Reducing atmosphere (hydrogen)** : removes the oxide layer on the powder surface and promotes bonding between particles.
- **Inert atmosphere (argon)** : prevents tungsten alloy from being corroded by reducing atmosphere at high temperature, suitable for alloys that are sensitive to composition.
- **Atmosphere purity control** : Use high-purity gas and equip with gas purification device to ensure extremely low oxygen content and prevent oxidation and nitridation.

- **Air flow and pressure** : Reasonably adjust the air flow rate and pressure to ensure a uniform atmosphere and heat conduction effect.

3.3.5 Sintering quality monitoring and testing

- Thermal analysis (such as differential thermal analysis DTA and thermogravimetric analysis TGA) is used to monitor the temperature and reaction characteristics of the sintering process.
- The sintering effect was evaluated by microstructure analysis, porosity determination and mechanical property testing.
- Monitor the atmosphere composition in real time to prevent the infiltration of impurity gases.
- The finished product size and deformation are tested to ensure that the product meets the design requirements.

summary

Sintering technology and atmosphere control are the core links in the preparation of tungsten alloy rods, which directly affect the density, microstructure and mechanical properties of the material. Selecting a suitable sintering method (atmosphere protection, vacuum or hot isostatic pressing), combined with precise process parameter control and atmosphere purification technology, can significantly improve the comprehensive performance and stability of tungsten alloy rods. In the future, with the development of equipment technology and material science, the sintering process will be more efficient and intelligent, providing a solid guarantee for the high-quality manufacturing of tungsten alloy rods.

3.4 Heat treatment and densification process optimization

tungsten alloy rods plays a vital role in improving the density of materials, optimizing microstructure and improving mechanical properties. Reasonable design and optimization of heat treatment process can not only effectively eliminate the residual stress during sintering, but also promote grain refinement and uniform distribution of alloy elements, thereby significantly improving the comprehensive performance of tungsten alloy.

3.4.1 Purpose and function of heat treatment

- **Stress relief** : The thermal stress generated during sintering and cooling is released through heat treatment to prevent cracking and deformation of the green body.
- **Densification promotion** : High temperature heat treatment promotes the diffusion process, fills micropores and increases material density.
- **Grain control** : control grain size, refine structure, improve toughness and strength.
- **Homogenization of alloy elements** : accelerate the diffusion of alloy elements and avoid composition segregation.
- **Improve mechanical properties** : such as increasing hardness, yield strength and ductility.

3.4.2 Main heat treatment process types

3.4.2.1 Solution treatment

- Heating at high temperature to the solution temperature (usually 1200~1400℃) allows the alloy elements to fully dissolve into the matrix.
- After keeping warm for a certain period of time, cool rapidly to lock in a uniform solid solution structure.
- Effectively improve the uniformity and mechanical properties of materials.

3.4.2.2 Timeliness Processing

- The precipitation of alloy elements and strengthening phases are promoted by keeping the alloy at medium and low temperatures (500~800℃).
- Improve the hardness and strength of the material while maintaining appropriate ductility.
- Reasonable selection of aging temperature and time is the key to performance optimization.

3.4.2.3 Annealing

- Low temperature annealing is used to eliminate internal stress and improve material toughness.
- The temperature is generally controlled at 600~900℃, and the insulation time is adjusted according to the thickness of the material.
- Suitable for improving subsequent processing performance.

3.4.3 Optimization of heat treatment process parameters

- **Temperature control** : Precisely control the heating temperature to prevent overburning or insufficient temperature.
- **Heating rate** : Slow heating to avoid thermal shock and reduce the risk of cracks.
- **Holding time** : Ensure that the heat treatment effect is sufficient and avoid grain growth due to too long a time.
- **Cooling method** : Choose fast cooling or slow cooling according to performance requirements, which affects the material structure and performance.

3.4.4 Auxiliary technologies for densification process

- **Hot isostatic pressing (HIP) heat treatment** : sintering and densification are completed simultaneously under high temperature and high pressure, greatly improving the density of the material.
- **HIP + Heat Treatment Combination** : Maximize performance through HIP densification followed by targeted heat treatment.
- **Pulse heat treatment technology** : Use rapid pulse heating to promote diffusion, reduce heat treatment time and improve production efficiency.

3.4.5 Relationship between microstructure and performance

- Heat treatment promotes grain boundary diffusion, reduces porosity and improves bonding strength.
- Grain refinement helps to improve material toughness and impact resistance.
- Even distribution of alloying elements improves overall mechanical properties and corrosion resistance.

3.4.6 Quality control and testing methods

- Microscopy was used to analyze the microstructural changes before and after heat treatment.
- The densification effect was evaluated by density measurement and porosity analysis.
- Mechanical property tests verify the effect of heat treatment on strength, hardness and ductility.
- Stress testing (such as X-ray residual stress analysis) confirms the stress relief effect.

summary

Heat treatment and densification process are important technical links in the manufacturing of tungsten alloy rods . By scientifically designing heat treatment process parameters and combining advanced densification technology, the internal structure uniformity and mechanical properties of the material can be effectively improved to meet the strict requirements of high-end applications for the performance of tungsten alloy rods. In the future, with the development of new heat treatment equipment and intelligent control technology, the heat treatment process of tungsten alloy rods will develop in a more precise, efficient and environmentally friendly direction.

3.5 Machining and surface treatment technology (grinding, polishing, turning)

tungsten alloy rods usually need to be machined and surface treated to meet the design size and surface quality requirements. Due to the high hardness and brittleness of tungsten alloy materials, it is difficult to process. Reasonable selection and optimization of machining and surface treatment processes are of great significance to ensure product accuracy and performance.

3.5.1 Machining characteristics of tungsten alloy rod

- **High hardness and toughness** : Tungsten alloy has a hardness of HV300 or above and has good toughness, but at the same time the material is brittle and prone to cracks during processing.
- **Strong wear resistance** : Tools wear quickly when processing tungsten alloy, so high hardness and wear-resistant tools are required.
- **Good thermal conductivity** : It is conducive to the rapid dissipation of processing heat, but the high hardness leads to large cutting forces.
- **Processing difficulties** : Micro cracks, burns and surface roughness are likely to occur during the cutting process, and the processing parameters need to be strictly controlled.

3.5.2 Grinding

Grinding is the most commonly used finishing method in tungsten alloy rod processing , which is mainly used to improve dimensional accuracy and surface roughness.

- **Grinding tools** : Diamond grinding wheel or CBN grinding wheel is used, which is suitable for processing tungsten alloy due to its high hardness and wear resistance.
- **Grinding process parameters** :
  - Grinding wheel speed: Determined by material hardness and grinding wheel material, generally 20,000~40,000 rpm.
  - Feed speed: slow and even to prevent overheating and burns.
  - Cooling and lubrication: Use water-based or oil-based coolants to prevent material damage caused by excessive processing temperatures.
- **Grinding method** :
  - External cylindrical grinding is used for diameter machining of tungsten alloy rods.
  - Internal hole grinding is used to adjust the hole size.
- **Note** :
  - Control the grinding allowance to avoid cracks caused by over-processing.
  - Dress the grinding wheel regularly to maintain grinding efficiency and surface quality.

3.5.3 Polishing

Polishing is mainly used to improve the surface finish of tungsten alloy rods, reduce surface defects, and improve corrosion resistance and aesthetics.

- **Polishing material** : Use diamond polishing paste or alumina polishing agent, and select different particle sizes according to polishing requirements.
- **Polishing method** :
  - Manual polishing is suitable for small batches or special parts.
  - Mechanical polishing equipment is suitable for large-scale production, improving efficiency and consistency.
- **Polishing process** :

1. Rough polishing: remove large scratches and unevenness on the surface.
2. Fine polishing: further refine the surface and improve the smoothness.
3. Ultra-fine polishing: obtain mirror effect, surface roughness Ra can reach below 0.01μm.

- **Polishing Notes** :
  - Keep the polished surface clean to prevent scratches from impurities.
  - Control polishing time and pressure to avoid excessive wear of the material.

3.5.4 Turning

Turning is an important process for the shaping and dimension processing of tungsten alloy rods, and is suitable for the processing of shafts, cylinders and other shapes.

- **Tool selection** :
  - Use carbide tools or diamond tools to ensure sharp cutting and wear resistance.
  - The tool geometry parameters need to be optimized according to the characteristics of tungsten alloy to reduce cutting forces and vibrations.

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- **Processing parameters** :
  - The cutting speed is generally low, controlled at 20~60 m/min.
  - Feed rate and cutting depth are adjusted according to workpiece hardness and tool life.
  - Adequate cooling must be used to prevent thermal damage.
- **Turning method** :
  - Rough turning is used to quickly remove excess material.
  - Finish turning is used to achieve the designed dimensions and surface quality.
- **Turning Difficulties** :
  - chipping during cutting .
  - Prevent cracks or material peeling during processing.

3.5.5 Auxiliary role of surface treatment technology

- **Machining after heat treatment** : Heat treatment often causes dimensional changes, and machining can correct and improve dimensional accuracy.
- **Surface strengthening treatment** : Improve surface hardness and wear resistance through shot peening, laser surface treatment and other technologies.
- **Anti-corrosion coating** : A protective layer is applied on the surface of the tungsten alloy rod to enhance the corrosion resistance.

3.5.6 Quality control of machining and surface treatment

- **Dimension detection** : Use three-coordinate measuring machine (CMM), laser diameter gauge and other equipment to ensure dimensional accuracy.
- **Surface roughness detection** : Use a roughness meter to measure and ensure that the design indicators are met.
- **Microstructure inspection** : Analyze the changes in surface structure after processing and detect whether a heat-affected zone is generated.
- **Performance testing** : Mechanical properties and fatigue life testing to verify the impact of processing technology on material properties.

summary

Machining and surface treatment technology is an important part of the manufacturing of tungsten alloy rods. In view of the high hardness and high brittleness of tungsten alloy, the selection of appropriate grinding, polishing and turning processes, combined with optimized processing parameters and advanced equipment, can ensure the dimensional accuracy and surface quality of the product and meet the needs of high-end applications. At the same time, combined with surface strengthening and anti-corrosion treatment, the performance and life of tungsten alloy rods can be further improved.

3.6 New manufacturing technologies: extrusion, rolling, additive manufacturing

With the continuous progress of material science and manufacturing technology, although the traditional powder metallurgy process occupies a dominant position in the production of tungsten alloy rods , it also has some limitations, such as limited density and organizational uniformity, low forming complexity, etc. In order to meet the needs of high-performance tungsten alloy rods in aerospace, military, medical and other fields for complex shapes, high density and excellent mechanical properties, new preparation technologies such as extrusion, rolling and additive manufacturing have been gradually introduced and developed rapidly in recent years, greatly enriching the manufacturing methods of tungsten alloy rods.

3.6.1 Extrusion technology

Extrusion is a continuous forming process in which tungsten alloy billets are subjected to pressure through the die aperture at high temperature or room temperature to allow the material to flow plastically along the die aperture to obtain the desired cross-sectional shape and size.

Extrusion process characteristics

- **High plastic deformation** : Through large plastic processing deformation, the grains are refined and the mechanical properties of the material are improved.
- **Density improvement** : The extrusion process promotes internal pore closure and tissue densification.
- **Flexible shape** : various cross-sectional shapes can be processed to meet complex structural requirements.
- **High production efficiency** : suitable for continuous batch production of long bars.

Extrusion method

- **Direct extrusion** : The billet and extrusion direction are the same, the equipment structure is simple, and it is suitable for large-size materials.
- **Indirect extrusion** : the die moves and the billet remains stationary, which reduces friction and extrusion pressure.
- **Hot extrusion** : Extrusion at high temperature to improve material plasticity and reduce processing force.
- **Cold extrusion** : Extrusion at room temperature to improve the surface quality and mechanical properties of the finished product.

Extrusion process parameters

- Extrusion temperature, speed and die design have a significant impact on the quality of the finished product.
- The larger the extrusion ratio (cross-sectional area ratio), the more complete the deformation, and the better the material density and performance.
- Lubricants are used to reduce friction and improve surface quality.

Extrusion technology application

- Preparation of high strength and high density tungsten alloy rods, especially those with large size and complex cross-section.

- Through multiple extrusion processes, the grains are further refined to improve toughness and wear resistance.

3.6.2 Rolling technology

Rolling is a processing method that uses rollers to apply pressure to tungsten alloy bars to cause plastic deformation of the material, reduce the cross-sectional size, and improve the organizational structure.

Rolling process characteristics

- **Strong continuity** : suitable for mass production of bars and strips.
- **Grain refinement** : Plastic deformation promotes the formation of grain boundaries and improves material toughness.
- **High dimensional accuracy** : The size can be precisely controlled through multiple rolling passes.
- **Good surface quality** : The surface after rolling is relatively smooth, which is convenient for subsequent processing.

Rolling method

- **Hot rolling** : carried out at high temperature, the material has good plasticity and is easy to deform.
- **Cold rolling** : Processing at room temperature to increase surface hardness and strength, and improve mechanical properties.
- **Reverse rolling** : rolling in alternating directions to improve the uniformity of the structure.
- **Multi-roll rolling** : suitable for complex cross-section forming.

Rolling process parameters

- Rolling temperature and speed directly affect material structure and properties.
- The design of multi-pass rolling scheme needs to be scientific to control deformation and gap.
- Roller materials and lubrication technology ensure surface quality and equipment life.

Rolling technology application

- Prepare slender tungsten alloy rods, strips and sheets.
- Used for tungsten alloy products with high requirements on dimensional accuracy and surface quality.

3.6.3 Additive Manufacturing Technology (3D Printing)

Additive manufacturing technology, especially 3D printing technologies such as metal powder laser melting (Selective Laser Melting, SLM) and electron beam melting (EBM), provides a new path for the personalized customization and complex structure manufacturing of tungsten alloy rods.

Additive Manufacturing Features

- **Complex structure manufacturing** : complex geometric shapes that are difficult to form using traditional processes can be manufactured, such as inner cavities and grid structures.
- **High material utilization rate** : powder is directly formed to reduce material waste.
- **Large design freedom** : The design can be quickly adjusted according to demand, shortening the product development cycle.
- **Functional integration** : can realize the manufacturing of multifunctional composite structures.

Additive Manufacturing Process Challenges

- The high melting point and high thermal conductivity of tungsten alloy make it difficult to control the temperature of the molten pool.
- Rapid melting and cooling of powder by laser or electron beam can easily cause thermal stress and cracks.
- The flowability and distribution uniformity of powder have a significant impact on the forming quality.
- The equipment cost is high, the process parameters are complex, and special development is required for tungsten alloys.

Technological progress

- New high-energy beam sources and scanning strategies reduce thermal stress and improve forming quality.
- Powder pretreatment and atmosphere control optimization can reduce defects.
- Post-processing processes (such as hot isostatic pressing) are combined with 3D printing to improve material properties.

Application prospects of additive manufacturing

- Customized production of small batch and high complexity tungsten alloy parts.
- Rapid prototyping and functional test samples.
- Aerospace, nuclear industry, etc. have demands for complex structures and high-performance tungsten alloy parts.

summary

extrusion, rolling and additive manufacturing provide a variety of technical routes for the production of tungsten alloy rods . Extrusion and rolling technologies refine grains and increase density through plastic deformation, which are suitable for mass production and size control; while additive manufacturing has become the future trend of manufacturing complex tungsten alloy parts with its structural design freedom and material saving advantages. Combined with traditional powder metallurgy processes, the coordinated application of these new technologies will promote the development of tungsten alloy rod manufacturing towards high performance, multi-function and intelligence.

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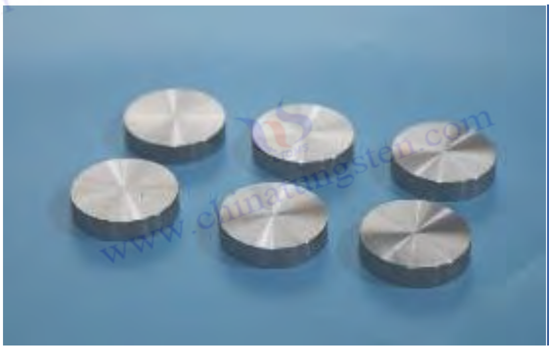
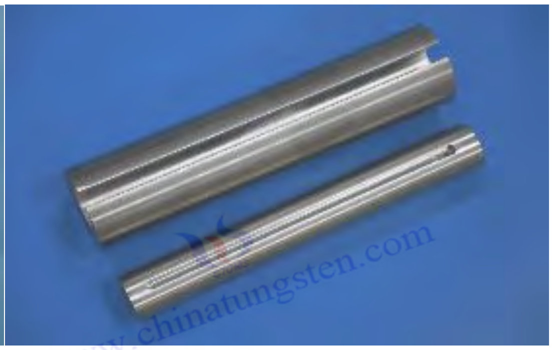

Chapter 4 Performance Testing and Quality Assessment of Tungsten Alloy Rods

4.1 Appearance and geometric dimension inspection

As a high-performance functional material, tungsten alloy rods are widely used in key fields such as aerospace, nuclear energy, medical, and military. Their appearance quality and geometric dimensional accuracy directly affect their subsequent processing, assembly, and performance. Therefore, appearance and dimensional testing is the first step in the quality assessment of tungsten alloy rods, and it is also an important link that must be passed before the product leaves the factory.

4.1.1 Basic requirements for appearance quality

tungsten alloy rods mainly focuses on whether there are visible defects on the surface that affect the use or reliability, and is evaluated according to relevant national standards (such as GB/T 21114, ASTM B777) or user-defined specifications. Common inspection contents include:

- **Surface finish** : The surface must be free of obvious scratches, pits, sintering cracks, metal flash, oxide scale and other defects.
- **Color and consistency** : The surface should have a consistent metallic luster and should not have any oxidation discoloration, stains, spots, etc.
- **Defect inspection** : Focus on the following typical surface defects:
    - o Micro cracks and fissures;
    - o Burrs and edge damage;
    - o Sintering holes or loose spots;

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  - Rust, discoloration or oil stains;
  - Local dents, warping, bending and other deformations.
- **End face condition** : Both ends should be flat, without flaked edges , cracks or obvious material shortages, and the verticality of the end faces should meet the standard requirements.

Detection tools and methods:

- **Visual inspection** : visual inspection or magnifying glass assisted inspection under natural light or standard lighting.
- **Illuminated observation platform** : Use a strong light background to check for small surface cracks or color differences.
- **Surface cleaner aid** : Observe the actual metal surface quality after removing surface oil and dirt.

Factory-level production often uses a combination of “full inspection + random inspection” to conduct appearance inspections, while 100% visual inspection is generally implemented for military or aerospace components.

4.1.2 Measurement items of geometric dimensions

Geometric dimension testing ensures that the tungsten alloy rod meets the accuracy requirements specified in the design drawings or contracts. Conventional measurement items include:

- **Length** : It can be fixed length or arbitrary length according to the design purpose of the bar, usually controlled with accuracy of ±0.5 mm or higher.
- **Diameter** : The roundness and tolerance of the bar are required to be high, and the precision application can be controlled within ±0.01 mm.
- **Ovality** : controls the difference between the two diameters of the cross section, generally not exceeding 0.05 mm.
- **Verticality/end flatness** : The end face of the tungsten alloy rod should be perpendicular to the center line of the rod.
- **Straightness (curvature)** : Measures the straightness deviation of the rod along its entire length, usually expressed in "mm/m", for example ≤0.5 mm/m.
- **Concentricity (if applicable)** : For hollow bars or turned structural bars, check the internal and external concentricity deviation.

Testing instruments:

- **Vernier calipers and micrometers** : used to quickly measure length and diameter, suitable for preliminary size confirmation.
- **Outside micrometer, inside micrometer** : used for high-precision diameter measurement.
- **Dial indicator + V-frame** : used to measure straightness and curvature.
- **Laser diameter gauge** : realizes non-contact high-precision online measurement, suitable for automated production lines.
- **Coordinate Measuring Machine (CMM)** : Used for precise inspection of complex geometric structures and providing full-size coordinate data.

4.1.3 Dimensional tolerance grades and standard basis

tungsten alloy rods varies according to product applications and international standards. Typical standard specifications include:

- **Chinese National Standard (GB/T 21114)** : specifies the diameter, length and tolerance grade of tungsten alloy rods of different sizes.
- **American Standard (ASTM B777) :** Detailed regulations on the dimensional control of high-density tungsten alloy products.
- **User-defined standards** : Aerospace and nuclear industry customers often require dimensions and geometric tolerances that are stricter than national standards.

Common dimensional tolerance reference:

Rod diameter range	Normal tolerance (mm)	Precision tolerance (mm)
≤10 mm	±0.10	±0.02
10–30 mm	±0.15	±0.03
>30 mm	±0.20	±0.05

4.1.4 Automated testing and data recording

With the development of Industry 4.0, more and more companies are introducing automated testing technologies to improve quality control efficiency:

- **Visual recognition system** : combines video and image recognition algorithms to achieve online appearance defect recognition.
- **Laser size scanner** : cooperate with the automatic feeding rack to realize the full automatic detection of bar length and diameter.
- **Quality database system** : record the test data in real time and upload it to the database to achieve batch traceability management.

4.1.5 Testing frequency and judgment criteria

The testing frequency is set according to production batch, usage and customer requirements:

- **Batch delivery** : Sampling inspection is adopted, such as AQL grading according to GB/T 2828.1 standard.
- **Military/nuclear energy use** : full inspection + random inspection, key dimensions and key indicators must be tested one by one .
- **Scrap and rework criteria** :
  - Products with penetrating cracks, deep scratches, large-area oxidation, and end-face blasting on the surface are judged as unqualified.
  - Dimensions that exceed the tolerance range and cannot be corrected through secondary processing are also judged as unqualified.

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summary

Appearance and geometric dimension inspection is the basic link of tungsten alloy rod quality control, which is related to the basic qualification of the product and affects the assembly adaptation and reliability of subsequent applications. With the introduction of automated testing methods and the improvement of testing standards, modern tungsten alloy rod manufacturing companies are moving towards higher quality consistency, faster testing efficiency and more complete traceability management.

4.2 Density and microstructure analysis methods

Density and microstructure are important indicators for measuring the uniformity, density and process maturity of tungsten alloy rod materials , and have a direct impact on their mechanical properties, thermal properties and service life. Density testing can indirectly determine the sintering density and pore distribution; microstructure analysis can reveal key information such as grain structure, phase distribution, and pore defects. Therefore, establishing a systematic density and organization evaluation mechanism is a key link to ensure high-quality production of tungsten alloy rods.

4.2.1 Significance and methods of density detection

tungsten alloy rods is usually calculated based on their chemical composition. For example, in W-Ni-Fe or W-Ni-Cu systems, the theoretical density can reach 17.0~18.5 g/cm³. The actual product density, uniformity, and closeness reflect its sintering quality, densification level, and existing defects (such as closed pores, inclusions, debonding , etc.).

(1) Archimedes method (liquid drainage method)

Principle : According to Archimedes' principle, the difference between the sample weighed in air and in liquid can be used to calculate the volume, and the density can be obtained by combining the mass.

step :

- Use deionized water or ethanol as the immersion liquid;
- Weigh the dry weight (W1) and the weight in the immersion solution (W2);
- Calculate the density: $\rho = W1 / (W1 - W2) \times \rho_{liquid}$.

Advantages : Easy to operate, suitable for most solid samples.

Limitations : Inaccurate for samples with closed pores or imperfect surfaces.

(2) Helium pycnometer method (gas replacement method)

Principle : By measuring the pressure difference between the sample chamber and the reference chamber , the sample volume and density are calculated.

Advantages :

- High accuracy (up to ±0.001 g/cm³);

- Can detect microporous materials;
- Suitable for high-end precision tungsten alloy products.

Representative equipment : AccuPyc , Micromeritics and other automatic gas densitometers.

(3) X-ray calculation method (voxel density)

Combined with industrial CT or X-ray scanning equipment, the voxel density of the sample is calculated through image reconstruction, which is suitable for structural parts with complex shapes or that cannot be touched.

4.2.2 Purpose and key indicators of microstructure analysis

tungsten alloy reflects its evolution characteristics during sintering, heat treatment and subsequent processing. The following key indicators can be evaluated through microscopic analysis:

- Grain size and distribution;
- Alloy element phase (W phase, Ni/Fe/Cu based phase) distribution and phase boundary clarity ;
- The number and morphology of pores or inclusions;
- tissue uniformity and directionality;
- Second phase precipitation and eutectic structure characteristics.

4.2.3 Microstructure analysis techniques

(1) Optical metallographic microscope (OM)

use :

- Observe the grain morphology, pores, and macroscopic structure;
- Phase boundaries can be visualized with standard etching solutions.

Sample preparation process :

- Inlay, grinding and polishing;
- Chemical etching (common reagents: iron chloride-hydrochloric acid solution);
- Select the appropriate magnification for observation.

(2) Scanning electron microscopy (SEM)

Advantages :

- High resolution, capable of observing nanoscale structures;
- Can be combined with energy dispersive spectrometer (EDS) to analyze element distribution;
- Detect micro defects such as sintering holes, crack initiation sources, and interface bonding.

Scope of application :

- Alloy interface research, grain boundary structure, and microcrack identification;
- Analysis of local segregation and diffusion behavior of alloying elements.

(3) Transmission electron microscopy (TEM)

use :

- Study the precipitation phase, dislocation, micro grain boundary, etc. in tungsten alloy;

- Analyze nanoscale strengthening mechanisms, amorphous phases, and interfacial reaction layers.

limit :

- The sample preparation is complex and is suitable for scientific research or high-end material development.

(4) Energy Spectroscopy (EDS / WDS)

- **EDS** : Rapid elemental analysis, used in conjunction with SEM;
- **WDS** : used for high-precision, low-content element detection (such as oxygen and carbon impurities);
- Used to analyze the composition of each phase and the uniformity of element distribution within the organization.

(5) X-ray diffraction (XRD)

Purpose :

- Identify the crystal structure and phase types present in tungsten alloys;
- Detect whether there are impurities such as oxides and carbides;
- The content ratio of the main phase and the secondary phase can be quantitatively analyzed.

4.2.4 Organizational defects and quality assessment criteria

Common microstructural defects include:

- Sintering holes or residual pores;
- "Core-shell" structure caused by element segregation;
- Unbonded particles or weakly bonded sintering interface;
- The second phase is unevenly distributed or excessively precipitated;
- Coarsening of grains due to heat treatment.

Judgment criteria :

- GB/T 13298 (General rules for metallographic structure analysis);
- ASTM E1245 (Evaluation of inclusions in metals);
- Enterprise internal control standards: usually set acceptable ranges for porosity, grain size and inclusion grade.

4.2.5 Analysis of the relationship between density and organization

Density testing and organizational observation verify each other and are important means of evaluating the quality of tungsten alloy products.

- High density often corresponds to sufficient sintering and low porosity;
- Good uniformity of organization and fine grains lead to superior mechanical properties;
- If the density is low and the structure shows a large number of closed pores, it may be due to insufficient sintering temperature or poor powder compaction;
- If the density is qualified but there is structural segregation, it may be caused by uneven distribution of raw materials or uneven heat treatment.

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summary
Density and microstructure analysis are the core links of tungsten alloy rod quality assessment, which can fully reflect the internal structural characteristics and density of the material. Accurate density measurement is achieved through Archimedes method, gas specific gravity method, X-ray method, etc., and in-depth research on organizational morphology and composition is carried out by combining optical microscopy, SEM, EDS, XRD and other means, which can not only ensure that the product meets the technical standards, but also provide a scientific basis for process optimization and new material research and development. With the popularization of high-resolution testing instruments and the introduction of automated testing platforms, the organizational control and quality assurance of tungsten alloy rods are gradually moving towards a higher level.

4.3 Mechanical Properties Test Standards (ASTM, GB, ISO)

As a functional structural material with high specific gravity and excellent toughness, the mechanical properties of tungsten alloy rods directly determine their service safety in harsh environments such as high stress, high load, and high impact . Parameters such as tensile strength, yield strength, elongation, hardness, impact toughness, and fatigue life are the key basis for measuring their quality and engineering applicability. In order to ensure the scientificity and comparability of the test results, mechanical properties testing must be carried out in strict accordance with the internationally accepted standard system (ASTM, GB, ISO).

4.3.1 Tensile properties test

the most basic and common method for testing the mechanical properties of tungsten alloy rods . By applying axial tension, the stress-strain behavior before fracture is measured to obtain core indicators such as tensile strength, yield strength, and elongation.

Test standards and applicable scope:

- **ASTM E8/E8M** "Standard Method for Tensile Testing of Metallic Materials": Applicable to metal bars, plates, and small-sized specimens;
- **GB/T 228.1** "Tensile test of metallic materials - Part 1: Test method at room temperature": This is the general national standard of China;
- **ISO 6892-1** "Tensile tests on metallic materials - Part 1: Test methods at room temperature": internationally accepted standard, basically equivalent to GB.

Key parameter definitions:

- **Tensile strength (UTS)** : The maximum stress that a material can withstand, in MPa;
- **Yield strength (YS)** : the minimum stress at which a material undergoes plastic deformation;
- **Elongation (El)** : The elongation of the specimen before fracture, which measures the toughness of the material;
- **Sectional shrinkage rate (Z)** : The degree of necking at the fracture, reflecting plasticity.

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Sample preparation and condition control:

- Sample shape: standard round bar (such as Φ6~Φ12 mm) or flat bar;
- Loading rate control: such as 0.5~2 mm/min;
- Temperature conditions: usually room temperature (20±5°C), high temperature stretching can be performed if necessary.

Note:

- tungsten alloy, the clamping part should be designed to prevent slipping or stress concentration;
- An electronic universal testing machine with high rigidity and a loading accuracy of ±1% must be used;
- After stretching, fracture photos need to be taken for fracture mechanism analysis.

4.3.2 Hardness test

Hardness is an important indicator for evaluating the ability of tungsten alloy to resist local plastic deformation and is widely used in process control, product grading and quality sorting.

Common test methods and standards:

- **Brinell hardness (HB)** :
  - Suitable for medium and low hard tungsten alloys;
  - Standard: ASTM E10 / GB/T 231.1;
  - Load range: 5003000 kgf , ball head diameter 2.510 mm.
- **Rockwell hardness (HRC/HRB)** :
  - Suitable for surface hardness testing of finished bars;
  - Standard: ASTM E18 / GB/T 230.1;
  - tungsten alloy is usually between 6080 HRB, or up to 2040 HRC (some heat treatment states).
- **Vickers hardness (HV)** :
  - Used for micro-area or small-size tungsten alloy microhardness testing;
  - Standard: ASTM E384 / GB/T 4340.1;
  - Applications: interface, grain refinement , microalloy structure evaluation.

Other notes:

- It is required to polish the surface to a mirror finish before testing to ensure that the indentation is clear and measurable;
- The test point should be away from edges, cracks and pores;
- For high hardness tungsten alloy, it is recommended to use a hard indenter and a low load test solution.

4.3.3 Impact toughness test

Impact test evaluates the material's ability to absorb energy under dynamic loads, reflecting its ability to resist brittle fracture. It is an extremely important indicator of tungsten alloy in armor-piercing and dynamic load applications.

Common standards:

- **ASTM E23** / **GB/T 229** : Metal Charpy impact test standard;
- **ISO 148-1** : Impact test standard for metallic materials.

Sample requirements:

- Standard size: 55 × 10 × 10 mm with V-shaped or U-shaped notch;
- The notch size and processing accuracy must be strictly controlled;
- Number of samples: Usually 3 pieces per batch are averaged.

Special instructions:

- Tungsten alloys often show low impact absorption energy (<10 J) due to their high brittleness;
- In order to improve toughness, ultrafine grain or microalloying design is generally adopted;
- After impact, the fracture surface can be analyzed by metallography or SEM to identify brittle/ductile fracture modes.

4.3.4 Fatigue and creep performance test (optional)

In some extreme service conditions (such as aerospace inertial systems and nuclear reactor components), tungsten alloy rods are also required to have excellent fatigue resistance and high temperature creep stability.

Related standards:

- **ASTM E466 / GB/T 3075** : Metal fatigue test method (high cycle fatigue);
- **ASTM E139 / GB/T 2039** : Metal creep test method (constant stress at high temperature).

Application Description:

- Fatigue testing is used to evaluate the life of materials under cyclic stress;
- Creep tests are often set at high temperatures (800-1000°C) and constant loads;
- Both are often used in nuclear energy, deep space exploration, and hypersonic weapons material development.

4.3.5 Criteria for judging mechanical properties test results

Different standards have different requirements for the mechanical properties of tungsten alloy rods. For example:

project	General industrial grade	Military/Aerospace Grade	Medical/Nuclear Grade
tensile strength	≥700 MPa	≥900 MPa	≥1000 MPa
Elongation	≥5%	≥10%	≥12%

Hardness (HRB)	70~85	75~90	78~92
Impact toughness (J)	≥6 J	≥8 J	≥10 J

The specific judgment basis should refer to the product design drawings, technical agreements or bidding specifications.

summary

tungsten alloy rods must be strictly carried out in accordance with the international authoritative standard system to ensure the accuracy, traceability and universality of data for multinational projects. ASTM, GB, ISO and other standards cover the entire chain of testing content from tensile, hardness, impact to fatigue, creep, etc., and are the core basis for guiding the quality inspection and material selection of tungsten alloy rods. With the continuous expansion of high-end application fields, higher requirements are also put forward for the automation, digitization and precision of detection methods.

4.4 Metallographic analysis and microstructural characterization

Metallographic analysis and microstructural characterization are important means to evaluate the internal structure and performance potential of tungsten alloy rods. By observing and measuring the internal grain morphology, phase distribution, pores, inclusions and other characteristics of the material, the degree of densification of the powder metallurgy process, the diffusion uniformity of the alloy elements, the heat treatment effect and the organizational defects can be determined, and its service behavior and reliability can be further predicted. It is a key link in quality control, process optimization and new material research and development.

4.4.1 Purpose and significance of metallographic analysis

Metallographic analysis is not only an important means of basic research in materials science, but also plays the following key roles in the production practice of tungsten alloy rods:

- **Evaluate sintering quality and porosity** : observe pore distribution, size and morphology to determine the level of densification;
- **Determine grain size and uniformity** : small and uniform grains are often associated with high strength and toughness properties;
- **Identify the phase boundary structure** : The clarity of the interface between W particles and Ni-Fe/Cu matrix phase affects the overall mechanical properties;
- **Discover microscopic defects and inclusions** : including crack origin, unfused area, impurity accumulation and other issues;
- **Study element distribution and precipitation behavior** : analyze microstructural changes such as alloy element diffusion and second phase precipitation.

4.4.2 Sample preparation process

The high hardness and high density of tungsten alloys place high demands on metallographic sample preparation. The standard sample preparation steps are as follows:

1. **Cutting** : Use a low-speed diamond cutter to prevent overheating and micro-cracks;
2. **Mounting** : Use hot or cold mounting materials to fix the specimen, which is convenient for grinding operation;
3. **Rough grinding** : start with 120 grit sandpaper, and gradually grind to 800~1200 grit sandpaper to keep it smooth;
4. **Fine grinding and polishing** :
    - Use 3 μm , 1 μm , and 0.25 μm diamond polishing fluid;
    - There should be no scratches, oxidation spots, or brushed lines after polishing;
5. **Chemical Etching** :
    - Common etching solution formula (reference):
        - Hydrofluoric acid + nitric acid + water (dangerous, please pay attention to safety);
        - Iron chloride + hydrochloric acid + ethanol mixture;
    - The etching time is controlled within a few seconds to tens of seconds in order to reveal the grain interface and phase distribution.

4.4.3 Microstructure observation method

(1) Optical microscopy (OM)

- **Resolution range** : 0.5~1 μm ;
- **Main Applications** :
    - Grain observation and size measurement;
    - Porosity distribution and macro defect identification;
    - of phase boundary morphology and tissue distribution;
- The grain size and porosity can be automatically counted **with the image analysis software .**

(2) Scanning electron microscopy (SEM)

- **The resolution is better than 10 nm** , which is the core tool for tungsten alloy structure analysis;
- **Applicable content** :
    - High magnification observation of the interface between W particles and Ni-Fe/Cu matrix;
    - Detect micro cracks, micro holes, inclusions, lack of fusion and other defects;
    - Combined with energy dispersive spectroscopy (EDS) to analyze the spatial distribution of elements;
- **Fracture analysis** : used to determine brittle or ductile fracture characteristics (cleavage plane, dimple, quasi-cleavage structure, etc.).

(3) Transmission electron microscopy (TEM)

- **Ultra-high resolution (<1 nm)** ;
- **Research content** :

  - Grain boundary structure and dislocation distribution;
  - Interfacial reaction layer or second phase precipitation;
  - Atomic level structural analysis and crystal distortion research;
- **Application scope** : Mainly used in scientific research or tungsten alloy upgrade and development.

(4) Energy Spectroscopy (EDS / WDS)

- EDS is suitable for rapid multi-element qualitative and semi-quantitative analysis;
- WDS (wavelength dispersive spectroscopy) is suitable for fine trace element (such as O, C) analysis;
- Combined with SEM, it is used to study the distribution and diffusion uniformity of Ni, Fe, Cu, etc. in the tungsten matrix.

(5) X-ray diffraction (XRD)

- Used to confirm the crystal structure and phase types of each metal;
- Can detect whether there are impurities such as tungsten oxide and carbide;
- Supports grain size estimation and texture strength analysis (with directional scanning).

4.4.4 Grain size and phase composition evaluation criteria

Grain size assessment method:

- **GB/T 6394** "Method for determination of average grain size of metals";
- **ASTM E112** : Grain grade evaluation by standard comparison chart or image analysis;
- Fine grains are usually graded above grade 9 (corresponding to an average grain size of less than 15 μm);
- Uneven structure, coarse grains and grain boundary inclusions are unqualified items.

Phase analysis and quantitative methods:

- area ratio of each phase after partitioning the optical or SEM image ;
- Grayscale segmentation and distribution measurement of typical W phase/Ni-Fe base phase ;
- EDS combined with image analysis software can achieve regional component quantification.

4.4.5 Analysis of the relationship between microstructure and performance

Microscopic features	Impact on performance
Small and uniform grains	Improve strength and toughness, reduce crack sources
W particle distribution is uniform	Conducive to impact resistance and uniform load transfer
W/Ni-Fe interface is tightly bonded	Improve overall plasticity and impact strength
High porosity or uneven distribution	Reduce strength and density, and easily become the origin of cracks

Micro cracks/inclusions exist	May cause premature fracture and reduce fatigue life
Precipitation of coarse second phase	May become a stress concentration point, resulting in a decrease in mechanical properties

summary

Metallographic analysis and microstructural characterization are indispensable means for tungsten alloy rods from raw material control to final product performance verification. Through the combination of optical microscopy, SEM, TEM, XRD and other technologies, we can not only gain an in-depth understanding of the organizational evolution laws and microscopic defects inside tungsten alloys, but also provide strong technical support for production optimization and new product design. With the development of image recognition and AI-assisted analysis technology, metallographic analysis of tungsten alloys is evolving towards automation, quantification and intelligence.

4.5 Chemical composition analysis (ICP, XRF, ONH)

tungsten alloy rods directly determines its performance upper limit and reliability. In high-density tungsten alloys such as W-Ni-Fe and W-Ni-Cu, the proportion of main elements (such as tungsten content is usually 85%~98%), impurity control (such as C, O, N, H, P, S) and trace elements (such as Cr, Co, Mo, etc.) have a significant impact on the physical, mechanical, processing and service properties of the alloy. Therefore, establishing an accurate and comprehensive chemical composition analysis system is the basic link to ensure product quality and meet standard specifications and customer requirements.

4.5.1 Importance of chemical composition analysis

tungsten alloy rods include:

- **Confirm whether the alloy grade meets the standard** (such as A, B, C in ASTM B777 standard);
- **Verify the stability of ingredients and smelting process** ;
- **Control the content of harmful impurities (such as O, N, C, S, P) to avoid brittleness and crack tendency** ;
- **Analyze the abnormal composition of failed products** ;
- **Supports material traceability and batch quality control** .

4.5.2 Overview of mainstream chemical analysis methods

Method Category	Analysis object	Features
ICP-OES / ICP-MS	Metal elements (main component + trace amount)	High sensitivity, suitable for simultaneous analysis of multiple elements

XRF (X-ray fluorescence spectroscopy)	Metal main component	Fast and non-destructive, suitable for factory site or batch analysis
ONH analysis	Oxygen, nitrogen, hydrogen	High temperature pyrolysis method, suitable for tungsten and its alloys
CS Analyzer	Carbon, sulfur	Arc combustion method, fast and efficient
Wet chemical analysis	Specific elements	High accuracy, but low efficiency and high risk of contamination

Specific standards should refer to:

- ASTM B777, B702;
- GB/T 21114, GB/T 38792;
- Customer or military/aerospace standards.

summary

tungsten alloy rods covers macro-main elements, trace impurities and trace gas elements, and is the core means of evaluating the stability, purity and consistency of alloys. Modern detection technologies such as ICP-OES, XRF, and ONH analyzers can achieve high-precision, high-throughput, and automated composition control, greatly improving quality control efficiency. In the future, with the development of intelligent manufacturing, these technologies will also be more widely used in online monitoring, batch traceability, and closed-loop process optimization.

4.6 Surface Roughness and Defect Detection (Visual Inspection, CT)

tungsten alloy rods, its surface quality not only directly affects the service life, matching accuracy and appearance grade of the material, but is also closely related to the heat dissipation performance, stress concentration, fatigue crack initiation, etc. in subsequent applications. Therefore, surface roughness control and defect detection are important links that cannot be ignored in the quality assessment of finished products. With the continuous development of detection technology, traditional manual visual inspection has gradually been combined with high-end means such as digital imaging, 3D CT, and laser contour scanning to achieve efficient, automated, and precise detection processes.

4.6.1 Significance and index definition of surface roughness testing

Surface roughness is an important parameter that characterizes the degree of microscopic unevenness on the workpiece surface. Roughness not only affects the assembly, friction, wear, thermal conductivity and fatigue performance of tungsten alloy rods, but also affects the adhesion and corrosion resistance of coatings.

Common roughness parameters (according to GB/T 3505, ISO 4287):

Parameter name	meaning	unit
Ra	Arithmetic mean roughness, the most commonly used indicator	μm
R	Maximum height (average of five points)	μm
R	Total height (the difference between the highest peak and the lowest valley)	μm
R	RMS roughness (more sensitive to spikes)	μm

4.6.2 Surface roughness testing methods and equipment

(1) Contact roughness tester

- **Principle** : The probe is moved along the surface to record the contour changes;
- **Representative equipment** : Japan Mitutoyo SJ-210, Germany Mahr Perthometer ;
- **Advantages** : Accurate measurement, suitable for batch standard parts;
- **Limitations** : Not suitable for soft or highly reflective surfaces, contact operation required.

(2) Non-contact laser confocal or white light interferometer

- **Principle** : Use laser/white light interferometry to construct a 3D contour map;
- **Advantages** :
    - Non-contact, non-destructive testing;
    - High precision (nanometer level);
    - Can quickly scan large areas;
- **Representative devices** : Keyence VK-X series, Zygo Nexview , Sensofar .

(3) 3D profile scanner/structured light projector

- **Application** : It can be used to detect the overall surface profile consistency, steps, pits, etc. of the bar;
- **Suitable for on-site batch testing or visually assisted quality inspection.

4.6.3 Surface defect detection technology and application

Defects that may occur during the forming or processing of tungsten alloy rods include:

- Surface cracks, scratches, and pits;
- Oxide layer, black spots, carbon residues ;
- Adhesions, peeling, pinholes;
- Geometric deformation or ovality out of tolerance.

(1) Visual Inspection

- **Standard** : Description of surface condition in GB/T 8170 / ASTM B777;
- **Method** : Naked eyes + magnifying glass (3X~10X);
- **Typical judgment rules** :
    - No cracks or peeling are allowed;

- Surface color difference and slight friction marks are acceptable (depending on the application level);
- The defect size in a specific area does not exceed a certain value (e.g. ≤0.5 mm).

(2) Digital camera + image recognition system

- Applied to online detection of assembly lines;
- With the help of machine learning algorithms, it can automatically identify scratches, holes, and color anomalies;
- The accuracy rate can reach over 95%, which is particularly suitable for large-scale appearance screening.

(3) Three-dimensional X-ray computed tomography (CT)

- **Principle** : Use X-ray multi-angle scanning to reconstruct a three-dimensional volume image;
- **Detectable content** :
  - Internal pores, inclusions, cracks, and looseness;
  - Surface crack depth and extension direction;
  - Uniformity of tissue at the center and edge of the rod;
- **Representative equipment** : Nikon, GE phoenix, Yxlon ;
- **Resolution** : up to 1~5 μm , suitable for analysis of high-end military products, nuclear energy, and aerospace tungsten alloy rods.

4.6.4 Defect level assessment and quality determination

The evaluation of various surface defects requires the formulation of judgment criteria according to the requirements of different application fields. The following is a reference classification:

Defect Type	Military/Nuclear Tungsten Alloy	Tungsten Alloy for Industrial Use
crack	prohibit	prohibit
Pits	≤0.3 mm	≤0.8 mm
Oxidation spots	Cannot exist	May exist slightly
Surface roughness	Ra ≤ 0.4 μm	Ra ≤ 1.6 μm

Relevant reference standards include:

- **GB/T 13306** : Terminology of metal surface defects;
- **ASTM E45/E1245** : Inclusion and defect detection method;
- **YS/T 582** : Tungsten alloy product quality inspection specification (industry standard).

4.6.5 Trends in Automation and Intelligent Testing

Modern tungsten alloy rod manufacturing companies are gradually introducing:

- **Online visual inspection system** : operates synchronously with the CNC machining center to achieve 100% real-time appearance quality inspection;
- **AI image recognition platform** : training defect feature models based on deep learning to improve recognition accuracy;

- **Full-size scanning and imaging modeling** : laser or white light scanning to obtain the complete bar surface topology;
- **Quality big data analysis** : defect tracking, equipment association, and process iteration optimization.

These technologies have greatly improved the detection efficiency and quality stability, helping the high-end tungsten alloy rod manufacturing to develop towards a "zero defect" direction.

summary

Surface roughness and defect detection are the key to the transition of tungsten alloy rods from "functional materials" to "precision structural components". Through contact/non-contact roughness measurement, CT imaging, visual recognition and other technical means, the surface quality and internal defects of the material can be fully understood. In the future, intelligent detection, automated quality control and data-driven defect prediction will become one of the core capabilities of high-end manufacturing of tungsten alloy rods.

4.7 Nondestructive testing technology (ultrasound, X-ray, magnetic particle)

Tungsten alloy rods are mostly used in high-reliability fields such as aviation, military, nuclear energy and medical, which place extremely high demands on their internal quality and structural integrity. Conventional destructive testing can obtain some mechanical and microscopic data, but it cannot fully evaluate the internal defects of the entire rod. Therefore, the use of **non-destructive testing technology (NDT, Non-Destructive Testing)** to identify and evaluate hidden defects such as cracks, holes, inclusions, and looseness in tungsten alloy rods is a necessary means to ensure product safety, reliability and service stability.

This section will systematically introduce the three typical non-destructive testing methods applicable to tungsten alloy rods: **ultrasonic testing (UT), radiographic testing (RT), and magnetic particle testing (MT)** .

4.7.1 Ultrasonic Testing (UT)

Principles and advantages:

Ultrasonic testing uses high-frequency sound waves (1~10 MHz) to propagate in the material. When encountering discontinuous structures such as interfaces, pores, and cracks, a reflected signal is generated, which is received and analyzed by the transducer to determine whether there are defects.

- **Suitable for internal defect detection of tungsten alloy** , especially pores, inclusions, and undensified areas;
- **Strong penetration and large detection depth** , suitable for medium and thick diameter bars (Φ6~Φ100 mm);
- **Automatic scanning and detection can be realized** .

Detection method:

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- Use longitudinal waves (straight probe) or shear waves (angle probe);
- Multi-channel system achieves full surface and multi-angle coverage;
- High-end equipment is equipped with **A-scan (amplitude vs. time) **and** C-scan (2D image)** capabilities.

Standard basis:

- **ASTM E114 / E2375** : Standard for ultrasonic testing of metallic materials;
- **GB/T 12604.1, GB/T 5777** : Ultrasonic testing method for metal forgings/bars.

Technical points:

- Tungsten alloy has a large acoustic attenuation, so a high-energy probe (such as 5 MHz) should be used;
- The detection sensitivity must be adjusted to be able to identify 0.2~0.5 mm defects;
- The surface needs to be polished to reduce the coupling layer error;
- After detection, the position, depth and amplitude of the defect reflection wave should be recorded to determine its level.

Defect identification diagram:

Defect Type	Ultrasound features
crack	Highly reflective signal with clear boundaries
Porosity	Moderately reflective, irregular shape
Lack of dense area	Layered echo, multiple reflections

4.7.2 Radiographic Testing (RT)

Principle and application:

Radiographic testing uses X-rays or gamma rays to penetrate materials. Different density or thickness areas have different radiation absorption capabilities. The radiation transmission image is recorded through an imaging plate (film or digital detector) to identify internal defects.

- **Applicable to the detection of density difference defects such as pores, cracks, inclusions, etc. in tungsten alloy rods** ;
- **Good resolution for near-surface or deep-seated defects** ;
- **Often used as a means of final quality assessment or high-level acceptance** .

Testing equipment:

- Industrial X-ray machine (tube voltage 160~320 kV);
- Isotope gamma sources (such as Ir-192) are used for thick-walled bars;
- Digital radiography system (DR/CR) can realize high-definition real-time images.

Technical indicators:

- Minimum detectable defect size: about 0.1~0.3 mm;
- Imaging clarity and detection sensitivity depend on radiation energy, exposure time and focal length;
- It is often necessary to verify the imaging resolution using a comparison test block (IQI).

Testing standards:

- **ASTM E1742, E1030** ;

- **GB/T 3323, GB/T 19802** ;
- The medical nuclear energy field also needs to meet higher standards such as ISO 5579 and EN 462.

Advantages and limitations:

advantage	limit
The detection images are intuitive and the records can be saved	High equipment cost and complicated operation
Porosity, cracks, and inclusions can be identified	Insensitive to low density difference defects
Can be used for final inspection and failure analysis	Limited penetration into thick and large pieces

4.7.3 Magnetic Particle Testing (MT)

principle:

When ferromagnetic materials are magnetized, if there are defects such as cracks, inclusions, and unfused materials on the surface or near the surface, these areas will generate magnetic leakage fields . After spraying magnetic powder, the magnetic powder will gather at the defects to form visible traces.

- **Suitable for rapid detection of surface/near-surface defects** ;
- It is mainly used for iron-containing tungsten alloy rods (such as W-Ni-Fe series), but not for W-Ni-Cu series.

Detection method:

- AC magnetization is used to detect surface defects;
- DC magnetization can detect slightly deeper defects (1~3 mm);
- Wet method (magnetic suspension) or dry method magnetic powder can be used;
- Black and white contrast fluid or fluorescent magnetic powder combined with ultraviolet light improves recognition.

Applicable standards:

- **ASTM E709** : General principles for magnetic particle testing techniques;
- **GB/T 15822, JB/T 6063** : Magnetic particle testing method and quality assessment;

Features analysis:

Advantages	Limitations
Low cost and fast detection speed	Ferromagnetic materials only (Ni-Fe system)
Defect positioning is intuitive and highly sensitive	Cannot detect deep or non-opening defects
Suitable for on-site batch operations	Powder residue and contamination risk need to be cleaned up

4.7.4 Defect grade assessment and nondestructive testing criteria

In order to ensure uniform quality assessment, it is necessary to determine whether the defects exceed the limit according to the relevant standards, for example:

Defect Type	Maximum permissible size (example, Φ20 mm rod)	Is it allowed?
crack	Not allowed to exist	no
Holes	≤0.3 mm, not dense	yes
Layering	Not allowed	no
Non-metallic inclusions	≤0.5 mm, evenly distributed	Depending on the level

Common grading standards:

- **ASTM B777/B702** : Reference standard for nondestructive testing of tungsten alloys;
- **GB/T 38561, GB/T 31928** : Special standards for tungsten alloy testing;
- **Customer Technical Agreement** : Customized standards for aviation, nuclear power, etc. are more stringent.

summary

tungsten alloy rods, non-destructive testing technology can identify internal and surface defects without destroying the material. Ultrasonic testing is suitable for the internal quality assessment of most rods; X-ray testing has obvious advantages in visual images and is a necessary means for high-end products; magnetic particle testing provides a highly sensitive identification capability for surface microcracks. The reasonable combination of the three can achieve multi-level and all-round quality assurance for tungsten alloy rods.

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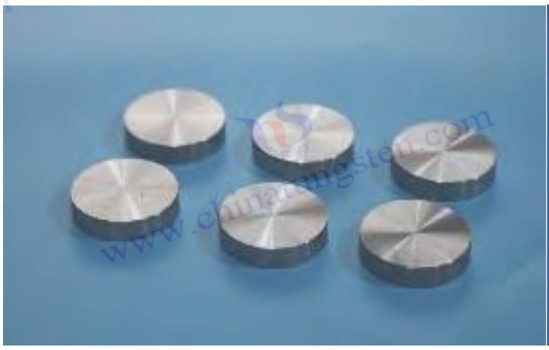
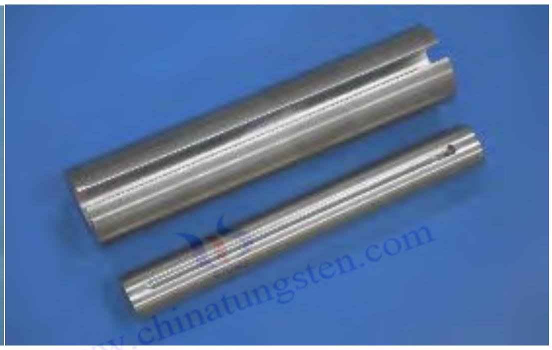

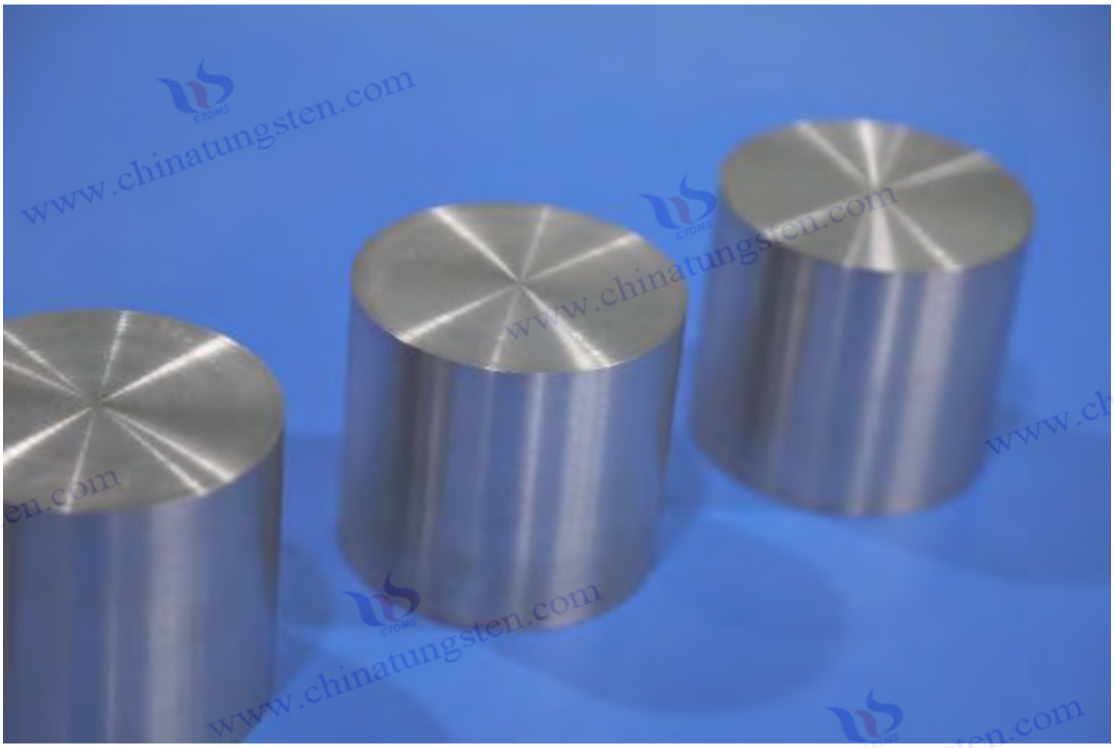

Chapter 5 Typical Application Fields of Tungsten Alloy Rods

5.1 Aerospace Counterweights and Inertial Components

Tungsten alloy rods have an irreplaceable and important position in the field of aerospace, and are particularly suitable for **counterweight systems** and **inertial components** . Due to its ultra-high density, good processability and excellent structural stability, tungsten alloy rods are widely used in mass balancing, kinetic energy regulation and attitude control systems in aircraft, satellites, missiles, drones and other aircraft, and are one of the important representatives of high-performance metal materials in the current aerospace industry.

5.1.1 Background and requirements for counterweight systems

In aerospace systems, counterweight assemblies are often used for the following purposes:

- **Center of gravity control** : In order to maintain the stability of the aircraft's attitude and the reasonable distribution of its moment of inertia, it is necessary to configure precision counterweights in the structural or power offset area;
- **Dynamic balancing** : In high-speed rotating structures (such as gyroscopes, motor rotors, flywheels, etc.), counterweights are used to fine-tune unbalanced torque to prevent resonance or fatigue;
- **Fuel consumption compensation** : As the use of liquid fuel decreases, the center of gravity of the aircraft shifts, and the balance is maintained by tungsten alloy dynamic weights;
- **Attitude Adjustment** : Some satellite/missile systems use sliding or movable tungsten weights for fine attitude control compensation.

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Due to limited space, aircraft design requires that the weight material **should be as heavy as possible per unit volume** , while having good **vibration resistance, structural stability and environmental adaptability** . The emergence of tungsten alloy rods just meets this demanding standard.

5.1.2 Material advantages of tungsten alloy rods

Tungsten alloy rods (typically W-Ni-Fe or W-Ni-Cu systems) have the following significant advantages over other metal materials:

Performance parameters	Tungsten Alloy Rod	lead	Stainless steel	Titanium Alloy
Density (g/cm³)	17.0–18.8	11.3	~7.8	~4.5
Strength (MPa)	700–1000	15–30	500–800	900–1100
Temperature stability	Excellent (>1200℃ no plasticity reduction)	Difference	good	excellent
Environmental protection/toxicity	Non-toxic and environmentally friendly	poisonous	Non-toxic	Non-toxic
Processing adaptability	good	easy	medium	Difficult to process

Therefore, tungsten alloy is an ideal upgrade option to replace traditional materials such as lead in aerospace counterweight systems.

Typical structure of tungsten alloy counterweight rod

counterweights for aerospace use often take the following forms:

1. **Standard round bar/square bar**
   - Used for gyro rotors, inertia rings or centralized weights at the bottom of fuel tanks;
2. **Threaded Rod/Bolt Tungsten Rod**
   - Easy to install or remove from the structure, often used for satellite counterweight or ground testing;
3. **Processable special-shaped blocks/inserts**
   - Customized slotting, punching or step structures according to the aircraft structure can be tightly embedded in the cabin ;
4. **Removable/sliding tungsten rod**
   - Applied to attitude control systems, the center of gravity can be adjusted by moving along the guide rail;
5. **Tungsten Alloy Thin Sheet/ Short Rod Insert**
   - Used for inertia adjustment of blades and rotor structures.

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5.1.4 Key performance requirements

Aerospace grade tungsten alloy rods must meet the following indicators:

- **Density** : ≥17.5 g/cm³, controlled within ±0.05 g/cm³;
- **Dimensional accuracy** : ±0.01~±0.05 mm, requires fine turning and grinding;
- **Mechanical properties** :
  - Tensile strength ≥750 MPa;
  - Elongation ≥10%, ensuring impact toughness;
- **Surface roughness** : Ra ≤ 0.8 μm (glossy surface requirement);
- **Magnetic requirements** : Some inertial systems require **low-magnetic or non-magnetic tungsten alloys** (W-Ni-Cu is better than W-Ni-Fe);
- **High temperature stability** : resistant to heat shock and no structural deformation;
- **Reliability** : Internal defects can be detected through non-destructive testing (ultrasound/radio).

5.1.5 Practical Application Cases

(1) Satellite inertia wheel and attitude controller

- Tungsten alloy rod is used as **momentum wheel core** or **gyro inertia ring** ;
- Increase inertia through high density and improve attitude adjustment accuracy;
- Many types of satellites in the United States and Europe use W-Ni-Fe high-density rods.

(2) Dynamic balancing weights for aircraft/UAVs

- Used for balance correction of wings, tail wing and propeller blades;
- Small tungsten rods can be inserted into the blades to fine-tune the weight;
- The UAV market is expanding, and the demand for precision small-sized tungsten rods is increasing.

(3) Missile tail compartment and guidance section counterweight

- In order to ensure a stable flight attitude, a tungsten rod is often installed at the tail section to balance the center of mass;
- in the slide rail structure realizes adaptive weighting;
- Requires high density, strong bonding and vibration resistance.

(4) Aircraft engine gyro components

- Tungsten weights are placed at both ends of the shaft to improve stability and response speed;
- Combined with the high-temperature alloy shell, it constitutes a dynamic inertia unit.

5.1.6 Analysis of alternatives with other materials

With the upgrading of environmental regulations and the increasing demand for aviation weight reduction, tungsten alloy rods are gradually replacing the following traditional weight materials:

Material	Reason for replacement
lead	Highly toxic, banned or restricted in use
steel	Low density, requiring a larger volume to meet the standard
Copper Alloy	High conductivity, may introduce electromagnetic interference
Ceramics	Very brittle, unable to handle vibration and shock loads

Tungsten alloy has significant advantages in weight accuracy, safety, volume control, and recyclability, and has become the mainstream choice for high-end aviation weight materials.

summary

Tungsten alloy rods have comprehensive advantages in aerospace counterweights and inertial components, such as high density, stable structure, high temperature resistance, and strong processing adaptability. They not only meet the stringent requirements of modern aircraft for mass center of gravity control, but also support a variety of integrated designs. They are the first choice for high-performance counterweight materials. In the future, with the development of intelligent aircraft, small satellites, and high-dynamic platforms, tungsten alloy rods will play a core role in more key structures.

5.2 Tungsten alloy rod for military equipment (armor-piercing core, missile tail compartment)

Tungsten alloy plays an extremely important role in military equipment due to its high density, high strength, high kinetic energy retention and excellent penetration ability. Tungsten alloy rods are mainly used in the military field to manufacture **kinetic energy armor-piercing projectile cores** , **missile tail compartment counterweights** , **deep penetration bomb structural components** , **high explosive shells** and **inertial flight system counterweights** , etc. Its performance directly affects the strike capability, flight stability and combat efficiency of the weapon system.

5.2.1 Core Advantages of Tungsten Alloy Materials for Military Applications

tungsten alloy in the military field are reflected in the following aspects:

Performance Indicators	Tungsten Alloy (W-Ni-Fe)	lead	steel	Uranium Alloy (DU)
Density (g/cm³)	17.0 ~ 18.8	~11.3	~7.8	~19.1
Tensile strength (MPa)	700 ~ 1000	Very low	500 ~ 800	800 ~ 900
Thermal stability	Excellent (>1200°C without softening)	Difference	medium	excellent
Toxicity/Environmental Safety	Non-toxic and environmentally friendly	poisonous	Safety	Strong radioactivity

Machinability	good	Easy to process	good	Very bad (oxidized and brittle)

Therefore, tungsten alloy is known as a " **non-toxic depleted uranium alternative material** " and is an important material basis for contemporary high-performance conventional kinetic weapons.

5.2.2 Tungsten Alloy Rod in Armor-Piercing Projectile

(1) Application background

Kinetic Energy Penetrator (KEP) relies on high-speed kinetic energy to penetrate armored targets. Its core component, the "core", must have:

- Extremely high density to increase kinetic energy;
- Extremely high strength and hardness to maintain penetration capability;
- Good toughness to prevent it from breaking in flight or disintegrating when penetrating armor;
- Excellent dynamic stability to reduce deformation and deflection.

Tungsten alloy core is usually made of W-Ni-Fe heavy alloy rod, which is made into tail cone or needle core structure through precision forming, heat treatment and machining.

(2) Core type and size parameters

Type of ammunition	Typical Tungsten Alloy Rod Diameter	Aspect Ratio	Elastic core structure
Tank main gun APFSDS	Φ18 ~ Φ30 mm	15 ~ 25	Tungsten alloy long rod + aluminum shell
Small caliber armor-piercing projectile	Φ5 ~ Φ15 mm	10 ~ 15	Solid tungsten rod or tungsten core steel shell
Deep-penetrating ammunition core	Φ20 ~ Φ60 mm	5 ~ 10	Solid heavy tungsten alloy cone head

(3) Material technical requirements

- **Density** : ≥17.5 g/cm³, preferably 18.0 ~ 18.5;
- **Tensile strength** : ≥950 MPa;
- **Hardness** : HRC ≥ 35;
- **Elongation** : ≥10%;
- **Microstructure** : dense and uniform, no pores, grain size controlled ≤ 10 μm ;
- **Non-magnetic or low-magnetic** (special guidance system requirements);
- **Non-destructive testing has verified that there are no defects such as internal cracks and interlayer delamination** .

(4) Overview of manufacturing process

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1. Raw material preparation: high purity tungsten powder + Ni/Fe alloy powder mixture;
2. Powder metallurgy pressing → high temperature liquid phase sintering;
3. Heat treatment tempering → precision turning → polishing;
4. Surface coating (Mo/Cr) or oxide layer treatment (heat protection, wear resistance);
5. Ultrasound testing and CT examination.

5.2.3 Tungsten alloy rods in missile tail compartment counterweight structure

Application Description:

- In long-range/medium-range tactical missiles or air defense missiles, the tail compartment (tail cone section) is often used to install counterweights to balance the center of mass distribution between the propulsion device and the warhead;
- tungsten alloy rod in the tail compartment also plays a role in **increasing the inertial stability of flight, improving the guidance accuracy and reducing the deflection of the projectile** ;
- Some high-precision missile systems use **adjustable tungsten rod counterweight modules** to adjust the guidance algorithm deviation.

Structure:

- Solid tungsten alloy cylindrical/stepped rod;
- Covered with insulating material or ceramic coating to prevent electromagnetic interference;
- Through-hole structures have built-in leads or sliding shafts.

Requirements and features:

- **High density consistency control accuracy (within ±0.03 g/cm³)** ;
- **High machining accuracy requirements** (precision matching with the tail cabin mechanism);
- Corrosion-resistant, impact-resistant, and long service life;
- The weight ratio and position can be pre-configured according to the flight simulation data.

5.2.4 Other military tungsten rod applications

- **Tungsten alloy bushings for explosively formed munitions (EFP)** ;
- **Tungsten alloy rods for high explosive shells** (to improve the directional energy of explosion);
- **Military inertial system gyro weights** ;
- **Depth charge high pressure resistant tungsten rod structural parts** ;
- **Tungsten alloy rods in military heat absorbing/blocking structures** (such as EMP protection).

5.2.5 Standards and Compliance System for Tungsten Alloy Military Products

Military tungsten alloy rods usually need to comply with the following standards and system certifications:

Standard/System	Contents
GJB/T 3765	Technical requirements for military tungsten alloys
MIL-T-21014	Technical Specifications of Tungsten Alloy Rods for US Army
ASTM B777 Class IV	Specifications of Ultra High Density Tungsten Alloy
National military standard GJB 9001C	Defense Quality Management System
ISO 10204 3.2	Military-grade third-party quality certification report
NADCAP / ITAR / AS9100	Requirements for materials used in aviation military products

In addition, high-grade products need to provide: furnace number traceability , original powder batch report, full process non-destructive testing report and full mechanical properties inspection data.

summary

Tungsten alloy rods have the dual functions of "penetrating the core" and "structural stabilization anchor" in military equipment, especially in the application of kinetic projectile core and missile tail compartment structure, giving full play to its material advantages such as high density, high strength and thermal stability. Driven by the trend of being able to replace depleted uranium, environmentally friendly and non-toxic, and controllable precision manufacturing, tungsten alloy has become an important strategic material for modern military precision strike and high-mobility flight systems.

5.3 Nuclear energy field (radiation protection rods, neutron absorption structures)

Tungsten alloy plays a vital role in the field of nuclear energy with its ultra-high density, excellent high temperature stability and good radiation protection ability. Especially in nuclear power plants, research reactors, nuclear power plants and nuclear waste treatment systems, tungsten alloy rods are widely used to manufacture **radiation shielding components** , **neutron absorption structures** , **nuclear fuel packaging protection components** , etc. Its comprehensive performance is far superior to traditional lead, steel and uranium materials.

5.3.1 Background and needs of application in the nuclear energy field

In nuclear energy systems, the main functions of tungsten alloy rods include:

- **Gamma ray and X-ray shielding** : Tungsten's high atomic number (Z=74) gives it excellent high-energy ray absorption capabilities;
- **Neutron absorption and thermal neutron shielding** : Although tungsten itself does not have a neutron capture cross section as good as boron or cadmium , tungsten alloy rods can carry neutron absorbers in composite structures, playing a dual role of structure + shielding;
- **Structural stability and high temperature strength retention** : Tungsten alloy maintains dimensional stability and mechanical strength in the high temperature and strong radiation

environment of the nuclear reactor , which is an important basis for the structural components of the nuclear energy system;

- **High thermal conductivity assists thermal management** : Tungsten's good thermal conductivity can efficiently conduct heat during nuclear reactions, avoiding thermal stress concentration that causes structural fatigue.

5.3.2 Analysis of the advantages of tungsten alloy radiation protection rods

Performance Project	Tungsten Alloy Rod	Lead protection materials	Uranium Alloy (DU)
Density (g/cm³)	17.0–18.5	~11.3	~19.1
Gamma ray shielding capability	Excellent (high Z, high density)	generally	Excellent (slightly better than tungsten)
Neutron shielding capability	Medium (B/Cd can be added in combination)	Difference	Normal (partially absorbed)
Thermal stability	Excellent (>1200°C stable)	Poor (softening at 100°C)	excellent
Toxicity and radioactivity	Non-toxic and non-radioactive	poisonous	Radioactive and difficult to recycle
Processing and recycling capabilities	good	Easy to deform and pollute	Difficult processing, large safety restrictions

Tungsten alloy rods have become an ideal solution to replace uranium alloys and lead materials due to their **environmental protection, safety** and **mechanical/radiation advantages** .

5.3.3 Typical structural forms of tungsten alloy rods for nuclear energy

1. **Shielding Rod**
   - Solid or hollow tungsten alloy rods are used for core periphery, channel shielding, etc. according to the required thickness;
   - Used in combination with stainless steel and beryllium copper shells ;
   - The general density requirement is ≥17.8 g/cm³.
2. **Neutron composite absorption structure rod**
   - The core is a tungsten alloy rod, the surface is sprayed or coated with B_4C, Gd_2O_3 , Cd materials;
   - Integrated absorption of thermal neutrons + blocking of gamma rays;
   - Used for reactor safety control rods, rapid shutdown rods, etc.
3. **High heat load structural rods**
   - The cooling fluid flows through the hollow structure of the tungsten alloy;
   - Used in heat dissipation support systems of nuclear power plants;

- o Requirements include high thermal conductivity, dimensional stability and corrosion resistance.

4. **Nuclear fuel transportation and storage shielding rods**
   - o Tungsten alloy rod is installed in the inner layer of packaging barrel/container;
   - o It plays the dual role of gamma ray shielding and mechanical impact resistance;
   - o Meets IAEA transport safety regulations.

5.3.4 Material performance requirements

Tungsten alloy rods for nuclear energy not only require high density and radiation absorption capacity, but also must maintain structural integrity and physical stability in extreme environments:

- **Density control** : ≥17.5 g/cm³, good uniformity required;
- **Dimensional stability** : No deformation in continuous service at 300°C~800°C;
- **Corrosion resistance** : resistant to deionized water, boric acid solution, steam, etc.
- **Thermal conductivity** : > 90 W/ m·K , reducing thermal gradient stress;
- **Strength requirements** : tensile strength ≥700 MPa, good impact toughness;
- **Irradiation stability** : No lattice structure destruction occurs after irradiation;
- **Neutron capture design** : high uniformity is required when composite doping with Gd, B, and Cd;
- **Lifespan and fatigue performance** : supports long-term continuous use >10 years.

5.3.5 Practical application cases

(1) Nuclear power plant core protection module

- Tungsten alloy rods form the gamma-ray shielding layer around the reactor core structure;
- Used in combination with graphite, water cooling, zirconium alloy, etc.
- A domestic third-generation nuclear power project has adopted tungsten alloy shielding to replace the lead layer.

(2) Research reactor control rods and safety rods

- A hollow tungsten alloy rod coated with B_4C powder structure is used as a control rod;
- When the nuclear reaction needs to be shut down quickly , the tungsten alloy rod can be inserted into the core to absorb energy and block gamma rays;
- Most scientific research nuclear reactors use "W-Ni-Fe/B_4C" composite materials as safety terminal components.

(3) Lining structure of nuclear waste dry storage container

- tungsten alloy protection rods is set on the outer layer of the nuclear waste dry tank ;
- Compared with lead lining, it provides stronger protection without the risk of leakage;
- It has the ability to withstand strong earthquakes and strong impacts .

5.3.6 Relevant standards and certification systems

Tungsten alloy rods are used in the field of nuclear energy and must meet the following international/industry standards:

Standard/System	content
ASTM B777	Classification and performance requirements of high density tungsten alloy
ISO 12749/BS EN 61331	Nuclear protection material performance evaluation standard
IAEA TS-G-1.1	Safety Guidelines for Packaging and Transport of Nuclear Materials
GB/T 24298	for nuclear energy tungsten alloy material properties and testing methods
CNNC/China National Nuclear Corporation Internal Standard	Nuclear grade material procurement and acceptance process standards

In addition, the export of products for nuclear purposes must also comply with the control provisions of the Nuclear Suppliers Group (NSG) and declare **an End-Use Statement for nuclear purposes** .

5.3.7 Development Trends and Technology Outlook

- **composite tungsten alloy structure** : Integrate tungsten alloy with B, Gd and other materials through co-sintering, hot pressing, nano-coating, etc. to improve the coordinated shielding ability of neutrons and gamma rays;
- **Modular nuclear shielding structure application** : Tungsten alloy rods are precision-processed and mechanically connected to form detachable and reconstructible shielding modules, which are suitable for mobile nuclear power plants and shipboard reactors;
- **Improvement of high temperature and high pressure service performance** : Develop high temperature resistant tungsten alloy formula and heat treatment process to meet the high energy conditions of future advanced nuclear reactors (such as fast reactors, ADS systems);
- **3D printed tungsten alloy nuclear components** : Additive manufacturing will be used to manufacture nuclear tungsten alloy components with complex geometry and cavity structure to reduce weight and improve heat dissipation performance.

summary

Tungsten alloy rods have multiple functions in the field of nuclear energy, such as structural support, radiation protection and thermal management. With its high density, environmental protection and safety, it has become one of the indispensable core materials in the nuclear energy system. With the growing global demand for clean nuclear energy and safe nuclear facilities, the application prospects of tungsten alloys in protective components and neutron control elements will be broader.

5.4 High-density structural rods for medical equipment (radiotherapy devices)

With the rapid development of modern radiotherapy technology, tungsten alloy has become a key material for radiation shielding and dose adjustment in medical equipment due to its high density, high absorption performance and good mechanical properties. The application of tungsten alloy rods in radiotherapy equipment (such as linear accelerators, gamma knife, CyberKnife, etc.) not only ensures the precise radiation control of the equipment, but also effectively protects medical staff and patients from unnecessary radiation damage.

5.4.1 Background of the application of tungsten alloy in radiotherapy equipment

Radiation therapy relies on high-energy X-rays, gamma rays or electron beams to precisely irradiate the tumor area. The shielding and adjustment structures in the equipment need to meet the following requirements:

- **Efficiently absorb radiation** to avoid radiation leakage;
- **The material has high density** , achieving maximum shielding effect within a limited volume;
- **Strong mechanical stability** , able to withstand equipment movement and vibration;
- **High processing precision** ensures accurate guidance of the radiation beam;
- **Biosafe** , non-toxic and harmless, in line with medical and health standards.

tungsten alloy (17.0-18.8 g/cm³) make it an ideal material for shielding gamma rays and X-rays, superior to traditional lead materials and more environmentally friendly.

5.4.2 Typical Application Locations of Tungsten Alloy Rods

1. **Protective shields and bushings for radiation therapy equipment**
   - Used around the linear accelerator tube to block scattered rays;
   - Precision machining ensures uniformity of radiation beam shape and dose.
2. **Counterweight and blade structure in regulating blades (multi-leaf diaphragm, MLC)**
   - MLC blades are usually made of tungsten alloy because of its high density, which can effectively block radiation and control the shape of the treatment area;
   - Tungsten alloy rods can be used to make the blade skeleton and counterweight to ensure smooth and precise blade movement.
3. **Radiation protection shielding wall and movable shielding panel lining**
   - High-density tungsten alloy rods or plates form a protective structure to block radiation penetration;
   - lightweight design, reducing weight and improving safety.
4. **Internal weight structure of the dosage adjustment device**
   - Adjust radiation dose and direction to ensure precise control of treatment;
   - Tungsten alloy rods meet the high requirements of mechanical design due to their stable size and good processability.

5.4.3 Key performance requirements

Tungsten alloy rods for medical radiotherapy equipment must meet the following technical indicators:

- **Density** : ≥17.5 g/cm³, ensuring sufficient radiation absorption capacity;
- **Dimensional accuracy** : ±0.01~0.03 mm, ensuring structural matching and radiation accuracy;
- **Mechanical properties** :
  - Tensile strength ≥700 MPa, able to resist stress generated during equipment operation;
  - Hardness ≥HRC 30, ensuring wear resistance;
- **Surface quality** : Ra ≤ 0.4 μm , to avoid affecting equipment movement and radiation transmission;
- **Non-toxic and harmless** : Comply with medical device safety standards and prevent leakage of harmful elements;
- **Environmental stability** : corrosion resistance, high temperature resistance (under normal working environment) and no deformation after long-term use.

5.4.4 Processing and manufacturing technology

Medical grade tungsten alloy rods are generally prepared by high-purity powder metallurgy technology, and then formed by precision machining. The key process links include:

- **Precision hot isostatic pressing (HIP)** ensures that the material is dense and free of pores;
- **CNC turning and grinding** to achieve complex shapes and high dimensional accuracy;
- **Surface polishing and cleaning** to remove processing marks and contamination;
- **Non-destructive testing** (ultrasound, X-ray) to ensure there are no internal defects;
- **Surface coatings** (such as oxide films or ceramic coatings) can improve corrosion resistance and biocompatibility.

5.4.5 Typical Cases

- **Tungsten alloy blades for linear accelerator multi-leaf aperture**
  - Made of W-Ni-Fe tungsten alloy, the blade density reaches 18.0 g/cm³;
  - The blade size is precisely controlled, and the millimeter-level adjustment can be achieved with the high-precision mechanical transmission system;
  - Greatly improve the positioning accuracy of treatment target area and patient safety.
- **Gamma Knife head protection shield**
  - of ultra-high density tungsten alloy, the thickness is only half of the lead protective material;
  - Through fine machining and heat treatment, long-term stability and protection performance are guaranteed;
  - Improve the portability of the device and reduce the overall weight.

5.4.6 Development Trends and Technology Frontiers

- **high performance tungsten alloy materials**
  - Nanoparticles reinforce tungsten alloys to improve strength and toughness and extend equipment life;
  - Low magnetic tungsten alloy meets the requirements of MRI compatibility.
- **Intelligent Manufacturing of Tungsten Alloy Blades**
  - Use additive manufacturing (3D printing) technology to manufacture complex structures and reduce weight;
  - Combined with laser processing, it improves surface quality and manufacturing efficiency.
- **Environmentally friendly alternative to traditional lead materials**
  - Tungsten alloy, as a non-toxic alternative material, complies with medical environmental protection trends and regulations;
  - Achieve safe treatment and recycling of medical waste.

summary

Tungsten alloy rods have become an indispensable core material for modern medical radiotherapy equipment due to their high density, high precision and excellent mechanical properties. Its advantages in radiation protection, dose adjustment and structural stability have greatly improved the accuracy and safety of radiotherapy technology. With the advancement of material science and manufacturing technology, the application of tungsten alloy in the medical field will become more extensive and in-depth.

5.5 Dynamic balancing rods and rotating inertia parts in high-precision instruments

Tungsten alloy rods are widely used in various high-precision instruments and equipment due to their high density, high rigidity and good machining performance, especially in rotating parts that require high-precision dynamic balancing and inertia control. Tungsten alloy rods can effectively achieve fine-tuning of mass distribution and optimization of dynamic performance, and improve the measurement accuracy and operation stability of the instrument.

5.5.1 Application Background and Importance

High-precision instruments such as gyroscopes, flywheel gyroscopes, aerospace navigation equipment, precision power systems and high-speed rotating machinery have extremely high requirements for dynamic balance and inertial performance. The main functions of dynamic balance bars and inertial parts are:

- Adjust the mass distribution of the rotating body, eliminate unbalanced torque, and reduce vibration and noise;
- Improve the stability and life of the rotating body, and avoid bearing wear and equipment failure caused by imbalance;

- Optimize instrument response performance and control accuracy by precisely adjusting the moment of inertia.

Tungsten alloy rods are ideal materials for manufacturing these key components due to their high density (17.0~18.8 g/cm³) and excellent mechanical properties.

5.5.2 Structure and design of dynamic balance bar

- **Material selection** : Mostly use W-Ni-Fe or W-Ni-Cu high-density tungsten alloys to ensure high density and sufficient mechanical strength;
- **Shape specifications** : Commonly cylindrical rods, stepped rods or special-section rods, which are easy to embed in mechanical structures to adjust mass distribution;
- **Dimensional accuracy** : The processing accuracy requirements are extremely high, and the dimensional tolerance is usually controlled within ±0.01mm to ensure the dynamic balancing effect;
- **Surface treatment** : Improve surface quality through polishing, nickel plating or coating to reduce friction and corrosion.

5.5.3 Performance requirements for rotating inertia parts

Rotating inertia parts usually need to have the following properties:

- **High density and uniformity** ensure accurate calculation of moment of inertia;
- **Good mechanical strength and toughness** , able to resist the centrifugal force generated during high-speed rotation;
- **Thermal stability** to ensure stable size and performance under long-term operation;
- **Corrosion resistance** , extending service life, especially in high humidity or corrosive environments.

not deform or fail when running at high speeds , thus maintaining the high-precision operation of the equipment.

5.5.4 Typical application cases

1. **dynamic**
   balance rods are widely used in the rotating parts of aerospace gyroscopes. By precisely adjusting the mass distribution, zero deviation and extremely low drift of the equipment can be achieved.
2. **High-speed rotating machinery**
   is used for dynamic balancing of high-speed motors and turbine blades, effectively reducing vibration and improving equipment reliability and life.
3. parts ensure smooth rotation and measurement accuracy in the rotating parts of **precision measuring instruments**
   such as electron microscope turntables and laser interferometers .

5.5.5 Production process and testing methods

- **Manufacturing process** : high-density tungsten alloy rods are prepared by powder metallurgy and formed by precision turning and grinding;
- **Heat treatment** : improve mechanical properties and internal structural uniformity;
- **Surface treatment** : anti-corrosion coating and polishing to increase service life;
- **Quality inspection** : Dynamic balancing tester, high-precision coordinate measuring machine and non-destructive testing technology are used to ensure zero defects.

5.5.6 Future Development Trends

- **Micro-nanostructured tungsten alloy** : improve mechanical properties and fatigue resistance;
- **Lightweight design : Reduce the amount of** tungsten alloy through structural optimization to achieve light weight and high strength;
- **Additive manufacturing technology** : realize integrated manufacturing of dynamic balancing parts with complex shapes;
- **Intelligent dynamic balancing system** : Combined with sensing technology, the position of the tungsten alloy dynamic balancing rod is adjusted in real time to improve the dynamic performance of the system.

summary

Tungsten alloy rods play a key role in the field of dynamic balance rods and rotating inertial parts in high-precision instruments. Their high density and excellent mechanical properties make the equipment run more smoothly and with higher precision. With the continuous advancement of material technology and manufacturing processes, tungsten alloys will play a greater potential in precision rotating machinery and high-end instruments.

5.6 Support and heat dissipation structures in the electronics industry and communication equipment

With the rapid development of electronic equipment and communication technology, the miniaturization, high power density and high-speed operation of devices have put forward higher performance requirements for materials. Tungsten alloy rods have become the key support and heat dissipation structural materials in the electronics industry and communication equipment due to their high density, high thermal conductivity and good mechanical strength, effectively improving the stability and thermal management efficiency of the equipment.

5.6.1 Application Background

the thermal management and mechanical support performance of materials :

- The equipment generates a lot of heat when working, and poor heat dissipation will lead to performance degradation or even damage;
- The support structure must withstand mechanical and thermal stresses and maintain device positioning accuracy;
- The material needs to have good dimensional stability and electromagnetic compatibility.

Tungsten alloy rods are an ideal choice to meet these needs due to their high density, excellent thermal conductivity and low coefficient of thermal expansion.

5.6.2 Main Applications of Tungsten Alloys in Electronic and Communication Equipment

1. **Heat dissipation support structure for high power devices**
   - Heat dissipation base and support for power amplifiers and RF modules;
   - tungsten alloy helps to quickly remove the heat generated by the device;
   - The high density and rigidity of the material ensure a stable structure and reduce the impact of vibration.
2. **Damping weights in microwave and millimeter wave communication devices**
   - through tungsten alloy counterweight;
   - Effectively control micro-motion and positional deviation of RF components.
3. **Heat sink materials in semiconductor packaging**
   - Tungsten alloy is used as heat sink for high-end chip packaging, which helps to improve the heat dissipation efficiency of the chip;
   - Take into account both mechanical strength and thermal expansion matching to prevent thermal stress from damaging the chip.
4. **Precision mechanical positioning and support parts**
   - Maintain the relative position and stability of tiny mechanical parts;
   - Commonly used in mechanical brackets and fixtures in fiber optic communication equipment and laser systems.

5.6.3 Key material performance indicators

- **Density** : ≥17.0 g/cm³, ensuring high rigidity and stability of the structure;
- **Thermal conductivity** : ≥120 W/(m·K), rapid heat dissipation;
- **Thermal expansion coefficient** : $\leq 6\times 10^{-6}$ /K, matching the thermal expansion of semiconductor materials;
- **Mechanical strength** : tensile strength ≥ 800 MPa, hardness ≥ HRC 30;
- **Dimensional accuracy** : processing accuracy reaches micron level to ensure assembly accuracy;
- **Surface roughness** : Ra ≤ 0.2 μm , to avoid stress concentration and thermal resistance;
- **Electromagnetic compatibility** : Low magnetic responsivity, reducing signal interference.

5.6.4 Processing technology and quality control

- **High-purity tungsten powder is prepared by powder metallurgy** to ensure the material is dense and uniform;
- **Hot isostatic pressing (HIP) and high temperature sintering** to improve mechanical and thermal conductivity;
- **CNC machining** to achieve complex structures and high dimensional accuracy;
- **Surface finishing** , including grinding and polishing, to reduce surface defects;
- **Multiple non-destructive testing technologies** (ultrasound, X-ray CT) ensure internal quality.

5.6.5 Typical Cases

- **5G base station RF power module heat dissipation bracket**
  - Tungsten alloy rods support high power amplifier modules to ensure heat dissipation efficiency and mechanical stability;
  - Improve equipment reliability and service life.
- **High-end server chip cooling module**
  - Use tungsten alloy heat sink structure to improve chip temperature control;
  - Reduce thermal stress and ensure long-term stable operation.
- **Laser Mechanical Support**
  - Tungsten alloy bracket ensures the stability of laser path;
  - Anti- vibration design reduces optical errors.

5.6.6 Development Trends and Technology Prospects

- **The thermal management performance of nanostructured tungsten alloy is improved** , achieving more efficient heat dissipation;
- **tungsten alloy and carbon-based materials** reduces the overall weight while ensuring heat dissipation performance;
- **Integrate additive manufacturing technology** to manufacture complex heat dissipation structures and device supports;
- **The intelligent heat dissipation system is combined with tungsten alloy materials** to achieve real-time temperature control and adaptive heat dissipation.

summary

Tungsten alloy rods are used in the support and heat dissipation structure of the electronics industry and communication equipment. Due to their high density, high thermal conductivity and mechanical stability, they greatly improve the performance and reliability of the equipment. With the continuous increase in the power density of electronic equipment and the trend of miniaturization, the role of tungsten alloy will become more important, helping the industry move towards efficient and intelligent development.

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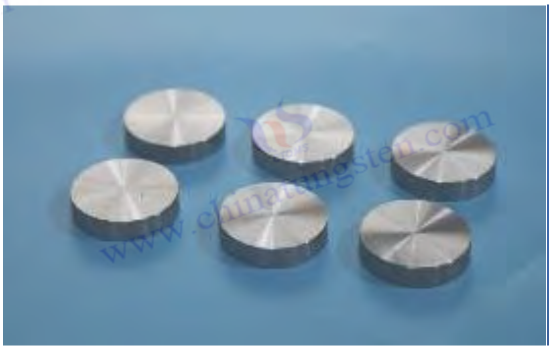
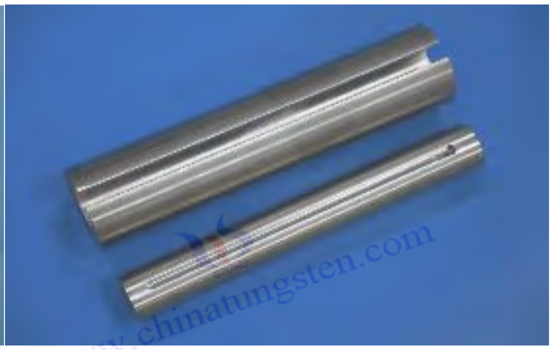

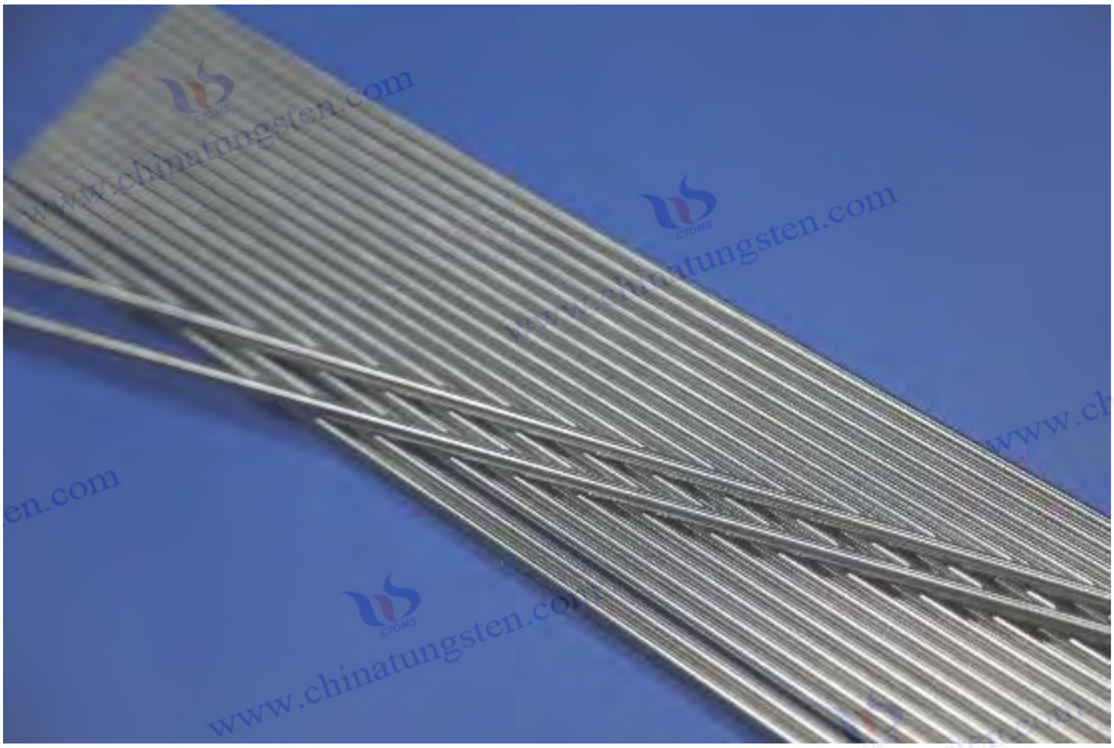

Chapter 6 Research, Development and Upgrading of Special Tungsten Alloy Rods

6.1 Nanoparticle Reinforced Tungsten Alloy Rod

As high-end equipment manufacturing and extreme working conditions put forward higher requirements for the performance of tungsten alloys, the bottlenecks of traditional tungsten alloys in strength, toughness and thermal stability are becoming increasingly apparent. Nanoparticle enhancement technology has become one of the key ways to break through the performance limits of materials. By evenly dispersing nano-scale reinforcement phases in the tungsten alloy matrix, the comprehensive performance of the material can be effectively improved, and the application field of tungsten alloys can be broadened.

Design Concept of Nanoparticle Reinforced Tungsten Alloy

Nanoparticle reinforced tungsten alloy rod is mainly based on the following design concepts:

- **Nanoparticle strengthening effect** : Nano-sized particles are evenly distributed in the matrix as the second phase, hindering grain boundary migration and dislocation movement, and improving strength and hardness;
- **Interface strengthening** : The nanoparticles and tungsten matrix are tightly bonded to form a strong interface, which improves the toughness and fracture toughness of the material;
- **Improved thermal stability** : Nanoparticles can pin grain boundaries, inhibit grain growth at high temperatures, maintain fine grain structure, and maintain high temperature performance;

- **Enhanced radiation resistance** : Nanoparticles act as capture points for radiation defects, increasing the service life of tungsten alloys in high-irradiation environments such as nuclear energy.

6.1.2 Commonly used nano-reinforced phase materials and their characteristics

Nanoparticle materials	Key Features	Advantages	Application Focus
Oxide nanoparticles (such as Y_2O_3, Al_2O_3)	Excellent thermal stability and chemical inertness	High temperature passivation, grain stabilization	High temperature corrosion resistant, high strength and toughness tungsten alloy
Carbide nanoparticles (such as WC, TiC)	High hardness, wear resistance	Significantly improve hardness and wear resistance	Tool materials, mechanical parts
Silicates and composite oxides	Good thermal expansion matching and better toughness	Reduce thermal stress and improve thermomechanical properties	Electronic packaging, thermally stable structures
Carbon nanotubes and graphene derivatives	High conductivity, high strength	Significantly enhanced strength and conductivity	Functional tungsten alloy, electromagnetic application

Preparation process of nanoparticle reinforced tungsten alloy

nanoparticle-reinforced tungsten alloy involves high-precision powder mixing and forming technology. The main processes include:

1. **Nanoparticle powder preparation and dispersion**
   - Nanoparticles are prepared by chemical precipitation, spray drying, mechanical alloying, etc.;
   - Ultrasonic dispersion and high-energy ball milling technology are used to evenly disperse nanoparticles in tungsten powder to avoid agglomeration.
2. **Powder mixing and pretreatment**
   - The nanoparticles and tungsten powder are fully mixed under an inert atmosphere to ensure a clean interface;
   - Dispersants and binders are added in some processes to improve powder fluidity.
3. **Forming and pressing**
   - Forming by cold isostatic pressing (CIP), die pressing or hot isostatic pressing (HIP);
   - Hot isostatic pressing can achieve a densified structure with high density and low porosity.
4. **Sintering and heat treatment**

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- o High temperature vacuum sintering promotes the interface bonding between tungsten matrix and nanoparticles;
- o Appropriate heat treatment can regulate grain size and strengthening phase distribution.

5. **Machining and surface treatment**
   - o Precision machining to obtain the required size and shape;
   - o Surface polishing and coating improve performance.

6.1.4 Performance Improvement Mechanism Analysis

- **Strengthening Mechanism**
  - o Nanoparticles act as barriers to prevent dislocation motion, significantly increasing tensile and yield strengths;
  - o Nanoparticles refine the grains, increase hardness and improve toughness;
  - o The particle-reinforced interface can effectively pin the grain boundaries and prevent high-temperature grain coarsening.
- **Thermal stability and corrosion resistance**
  - o The thermal stability of nanoparticles improves the high-temperature service capability of the material;
  - o The formation of a passivation layer inhibits oxidation corrosion and prolongs service life.
- **Radiation damage suppression**
  - o Nanoparticles capture radiation-generated defects, reducing dislocation slip and vacancy aggregation;
  - o Improve the irradiation stability of tungsten alloy in environments such as nuclear reactors.

6.1.5 Application Cases and Effect Verification

- **Tungsten Alloy Rod for Nuclear Energy**
  - o added nano Y_2O_3 particles shows better structural stability and radiation resistance under high temperature and irradiation conditions ;
  - o is more than 30% longer than that of traditional tungsten alloy.
- **High temperature aircraft engine parts**
  - o Nano- TiC reinforced tungsten alloy achieves significantly enhanced thermal fatigue resistance;
  - o The material strength is increased by 20%-40%, and the toughness is significantly improved.
- **Electronic packaging heat sink materials**
  - o Nano- Al_2O_3 reinforced tungsten alloy improves thermal conductivity and thermal expansion matching, reducing thermal stress ;
  - o Improved thermal stability ensures long-term stable operation.

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6.1.6 Development Trends and Challenges

- **Multi-component nanocomposite reinforcement system**
  - Combining multiple nanoparticles to achieve synergistic enhancement and reach the performance limit;
- **Nanoparticle interface engineering**
  - Optimize the interface structure between particles and matrix, and enhance the interface bonding strength and toughness;
- **Green and low-cost preparation technology**
  - Reduce the cost of nanoparticle preparation and compounding process and improve the feasibility of industrialization;
- **Precisely control the size and distribution of nanoparticles**
  - Real-time monitoring of microstructure for precise materials design using advanced characterization techniques.

summary

Nanoparticle-reinforced tungsten alloy rods significantly improve the strength, toughness, high temperature stability and radiation resistance of tungsten alloys by introducing high-performance nano-reinforced phases, providing a solid material foundation for the application of tungsten alloys in high-end fields such as nuclear energy, aerospace, and electronics. In the future, with the continuous advancement of nanomaterial preparation and composite technology, nanoparticle-reinforced tungsten alloys will show broader application prospects and more outstanding performance.

Design and performance improvement of microalloyed tungsten alloy rod

Microalloying technology is an effective way to improve the mechanical properties and thermal stability of materials by adding trace amounts of alloying elements to the tungsten alloy matrix to form fine second phase particles or solid solution strengthening. Compared with traditional alloying, microalloying has become an important strategy for optimizing the performance of tungsten alloy rods due to its small dosage, low cost and significant performance improvement.

6.2.1 Microalloying Design Concept

The core of microalloying is to achieve the following goals by adding trace alloying elements:

- **Solid solution strengthening** : Alloy elements are evenly distributed in the tungsten matrix in the form of solid solution, which increases lattice distortion and hinders dislocation movement;
- **Precipitation strengthening** : forming small and evenly distributed second phase precipitates, pinning dislocations and grain boundaries, and improving strength and toughness;

- **Grain refinement** : inhibit grain growth, optimize microstructure, and improve the comprehensive mechanical properties of materials;
- **Improve high temperature performance** : improve the thermal stability and creep resistance of materials and extend service life;
- **Optimize process adaptability** : improve the forming and processing performance of materials and reduce processing difficulty.

6.2.2 Commonly used microalloying elements and their action mechanisms

Alloying elements	Mechanism of action	Typical Effects
Titanium (Ti)	Form stable carbides or oxides and refine grains	Improve strength, toughness and wear resistance
Niobium (Nb)	Solid solution strengthening and precipitation strengthening	Improved high temperature strength and corrosion resistance
Vanadium (V)	Precipitation strengthening to form stable second phase particles	Improved yield strength and fatigue resistance
Aluminum (Al)	Solid solution strengthening, improving the uniformity of the structure	Enhance high temperature oxidation resistance and toughness
Zirconium (Zr)	Form stable oxide particles, pinning grain boundaries	Improve high temperature mechanical properties and antioxidant capacity
Copper (Cu)	Promote grain boundary strengthening and improve plasticity	Optimize processing performance and improve comprehensive mechanical properties

Preparation process of microalloyed tungsten alloy rod

1. **Alloy element selection and addition method**
   - Select appropriate elements and their contents (usually trace amounts, within the range of 0.1%-2%) according to target performance;
   - Use high purity alloy powder or element powder mixture to ensure uniform distribution.
2. **Powder mixing and homogenization**
   - High-energy ball milling, mechanical alloying and other technologies are used to achieve uniform mixing of alloy elements and tungsten powder;
   - Avoid excessive pulverization and agglomeration by controlling ball milling parameters.
3. **Forming and sintering**
   - Use cold isostatic pressing, molding and other methods to ensure density;
   - High temperature sintering process promotes the diffusion of alloy elements and the precipitation of the second phase.
4. **Heat treatment and machining**

- Appropriate heat treatment activates alloying elements and forms strengthening phases;
- Precision machining ensures final dimensions and surface quality.

6.2.4 Performance Improvement Effect

- **Significantly improved mechanical properties**
  - The tensile strength and yield strength are increased by 10%-30%, and some high-performance micro-alloyed tungsten alloy rods can even reach more than 1000 MPa;
  - Elongation and fracture toughness are improved, and impact resistance is enhanced.
- **Enhanced thermal stability and high temperature strength**
  - The precipitation strengthening of microalloying elements inhibits grain growth, and the material maintains a stable organizational structure at high temperatures;
  - Improved creep resistance, suitable for high temperature applications.
- **Improved corrosion and oxidation resistance**
  - Form a stable passivation layer to prevent high temperature oxidation and chemical corrosion;
  - Improve the service life and reliability of materials.
- **Processing performance optimization**
  - Microalloying elements improve powder fluidity and formability, reducing processing difficulty and cost.

6.2.5 Application Examples

- **tungsten alloy core material in the military field**
  - By adding trace amounts of Ti and Nb, high strength and toughness are achieved, and armor-piercing ability is improved;
  - Significantly improve the core's wear resistance and heat resistance.
- **Aerospace high temperature structural parts**
  - microalloyed tungsten alloy in high temperature parts of engines can extend the service life;
  - Maintain high temperature strength and reduce thermal fatigue damage.
- **tungsten alloy rods in medical radiotherapy equipment**
  - Adding trace amounts of Zr and V elements can improve wear resistance and corrosion resistance and extend equipment life.

6.2.6 Development Trends and Challenges

- **Fine control of micro-alloying element content and distribution**

- Use advanced characterization techniques to optimize alloy design and achieve precise performance control.
- **Study on the mechanism of multi-element synergistic enhancement**
  - Explore the synergistic effects among multiple micro-alloy elements to further improve performance.
- **Green and environmentally friendly preparation technology**
  - Develop low-energy consumption and low-pollution micro-alloyed tungsten alloy production process to meet environmental protection requirements.
- **Industrialization and large-scale application**
  - Solve the problems of cost and process complexity, and promote the widespread application of micro-alloyed tungsten alloys in more fields.

summary

Microalloying technology achieves multi-dimensional improvement in mechanical properties, thermal stability and processing performance of materials by adding trace amounts of functional alloying elements to tungsten alloy rods. This technology not only broadens the application scope of tungsten alloys, but also provides an effective path for the research and development of high-performance tungsten alloy materials. In the future, with the deepening of preparation technology and theoretical research, microalloyed tungsten alloys will usher in broader development prospects.

6.3 Composition Control of High Strength and Toughness Tungsten Alloy Rod

tungsten alloy rods are used in extreme working conditions such as aerospace, military industry, and nuclear energy, they usually need to have both high strength and high toughness. Traditional tungsten alloys focus on high strength, but lack toughness, which makes the material easy to break. The key strategy for preparing high-strength and tough tungsten alloy rods is to achieve an optimal combination of matrix and second phase by precisely controlling the alloy composition.

6.3.1 Basic principles for controlling the composition of high-strength and tough tungsten alloys

1. **Reasonable selection of main alloy element ratio**
   - The proportion of main elements such as nickel (Ni), iron (Fe), and copper (Cu) in the tungsten matrix determines the mechanical properties and organizational structure of the matrix;
   - Reasonably adjust the Ni/Fe ratio and copper content to strike a balance between strength and toughness.
2. **Introducing multiple alloy elements to achieve synergistic strengthening**
   - By adding trace amounts of microalloying elements such as titanium (Ti), zirconium (Zr), and vanadium (V), a strengthening phase is formed to achieve fine grain strengthening and precipitation strengthening;

  - The synergistic effect of multiple elements enhances interface bonding and improves overall toughness.
3. **Control the content of impurity elements**
  - Reduce impurities such as oxygen, carbon, and sulfur, avoid the formation of brittle phases, and improve material toughness.
4. **Optimize alloy composition gradient design**
  - The gradient alloy design is adopted to achieve zoned distribution of hardness and toughness and improve overall performance.

6.3.2 Effects of Composition Regulation on Tissue Structure

- **Solid solution behavior of tungsten matrix and alloying elements** The solid solution strengthening of alloying elements in tungsten matrix improves the strength, but excessive solid solution will reduce toughness, and the content needs to be precisely controlled.
- **Formation of the second phase precipitates**
  The carbide and oxide particles formed by the microalloying elements act as precipitation phases, refine the grains and hinder crack propagation.
- **Grain size and distribution**
  composition control affects the grain size and improves toughness and fatigue performance by inhibiting grain growth.

6.3.3 Typical high-strength and high-toughness tungsten alloy composition design

Ingredient system	Main Features	Performance
W-Ni-Fe-Cu-Ti-Zr	Multiple microalloying elements, grain refinement and precipitation strengthening	Strength increased by 20%-30%, toughness significantly improved
W-Ni-Fe-Cu-V-Al	Synergistic solid solution and precipitation strengthening, excellent fatigue resistance	Improved impact toughness and extended fatigue life
W-Ni-Cu-trace rare earth elements	Rare earth elements improve grain boundary bonding and prevent brittle fracture	Increased fracture toughness and enhanced heat resistance

6.3.4 Performance improvement mechanism brought by ingredient regulation

- **Interface strengthening and crack pinning**
  The tiny second phase particles enhance the bonding force of grain boundaries and prevent cracks from extending along grain boundaries.
- **Grain refinement and dislocation hindrance**
  composition regulation promote grain refinement, increase dislocation movement resistance, and improve strength and plasticity.

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- **Solid solution strengthening and toughness optimization**
  precisely control the content of solid solution elements to balance the relationship between strength and toughness.

6.3.5 Application fields and effect verification

- **Military** The high-strength and tough tungsten alloy rod **of the armor-piercing core material**
  significantly improves the penetration ability and wear resistance, and reduces the risk of brittle fracture.
- **of high-temperature resistant structural parts of aircraft engines**
  ensures both toughness and strength of materials in high-temperature environments, thereby improving safety.
- **of radiation-proof components of nuclear energy equipment**
  extends the service life and reduces maintenance costs.

6.3.6 Future Development Direction

- **Computational materials design**
  uses computational simulation to accurately predict the relationship between composition and performance, allowing customized high-strength and high-toughness tungsten alloys to be produced.
- **Advanced synthesis technology, combined with ingredient design**
  , heat treatment, hot isostatic pressing and other technologies, can enhance the effect of ingredient regulation.
- **Multi-scale structural regulation**
  from nano to macro levels to achieve performance optimization.

summary

The composition control of high-strength and toughness tungsten alloy rods achieves a synergistic improvement in strength and toughness by precisely designing the types and proportions of alloying elements and optimizing the microstructure. This strategy not only solves the bottleneck of tungsten alloy brittleness, but also lays a solid foundation for its wide application in extreme working conditions. With the advancement of material design theory and preparation technology, the performance of high-strength and toughness tungsten alloys will continue to break through, promoting the technological upgrading of related industries.

6.4 Study on Heat Treatment of High Temperature Resistant Tungsten Alloy Rods

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Tungsten alloy is widely used in high temperature environment due to its high melting point, high density and excellent mechanical properties. However, tungsten alloy is prone to grain growth, structural instability and performance degradation under extreme high temperature conditions. Heat treatment is a key process for regulating the microstructure and properties of tungsten alloy and an important means to improve the high temperature resistance of tungsten alloy.

6.4.1 Purpose and significance of heat treatment of tungsten alloy

- **Improve organizational uniformity** : Eliminate internal stress and make grain size uniform through reasonable annealing and aging processes;
- **Improve mechanical properties** : optimize grain size and second phase precipitation to enhance strength and toughness;
- **Stabilize high temperature performance** : inhibit grain growth, delay high temperature creep and softening;
- **Enhance corrosion resistance** : Improve the density and stability of the oxide film through surface heat treatment.

6.4.2 Commonly used heat treatment processes and parameters

Process Type	Temperature range (℃)	Insulation time	Main Function
annealing	800~1200	1~5 hours	Eliminate internal stress and refine grains
aging	500~900	2~10 hours	Promote the precipitation of the second phase and strengthen the matrix
Solution treatment	1200~1400	0.5~3 hours	Dissolve the phase and make the composition uniform
Surface heat treatment (nitriding/carburizing)	900~1100	1~4 hours	Improve surface hardness and oxidation resistance

6.4.3 Effect of heat treatment on microstructure

- **Grain size control:**
  Appropriate annealing temperature can refine the grains, prevent excessive grain growth, and maintain a balance between material strength and toughness.
- **Second phase precipitation and distribution**
  aging treatment promotes the fine and uniform precipitation of the strengthening phase and improves the effect of hindering dislocation movement.
- **Eliminate internal stress**
  The annealing process releases processing residual stress, reduces stress concentration, and reduces the risk of brittle fracture.

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6.4.4 Mechanism of improving high temperature resistance

- **Grain refinement strengthens**
  the fine and uniform grain structure to improve high temperature creep resistance and fatigue life.
- **The precipitated phase strengthens**
  the stable second phase particles and pins the grain boundaries, hindering grain boundary migration and improving high temperature strength.
- **Oxide film protection:**
  Surface heat treatment forms a dense oxide film, which blocks oxidation corrosion and improves antioxidant properties.

6.4.5 Typical research results and cases

- **High temperature annealing optimization**
  studies have shown that annealing at 1100°C for 3 hours can significantly refine the grains, increase the tensile strength of tungsten alloy by 15%, and increase the elongation by 10%.
- **Aging strengthening effect**
  After aging at 650°C for 6 hours, the strengthening phase precipitates evenly and the high temperature creep rate of the material is reduced by 20%.
- **Surface nitriding treatment**
  Surface nitriding treatment increases the hardness by 40%, the oxidation temperature by about 200°C, and significantly enhances the oxidation resistance.

6.4.6 Heat treatment process optimization strategy

- **The multi-stage heat treatment process design**
  combines annealing, solution treatment and aging to coordinately regulate the organizational structure.
- **Precise temperature control and atmosphere control**
  use vacuum or protective atmosphere to avoid secondary oxidation and ensure the heat treatment effect.
- **The heat treatment is linked with the forming process**
  to customize the heat treatment plan according to the characteristics of the previous forming process to avoid tissue damage.

6.4.7 Development Trends and Challenges

- **Intelligent heat treatment technology**
  uses online monitoring and control to achieve real-time optimization of the heat treatment process.

- **Long-term evaluation of high-temperature service performance**
  In-depth study of the influence of heat treatment on high-temperature creep and fatigue properties.
- Develop multi-scale simulation tools **by coupling microstructure and performance to guide heat treatment process design.**

summary

Heat treatment technology is the core link to improve the high temperature resistance of tungsten alloy rods . Through scientific and reasonable heat treatment process design, the microstructure can be effectively controlled, the strength, toughness and high temperature stability can be improved, and the stringent requirements of high temperature tungsten alloy materials in aerospace, nuclear energy and other fields can be met. In the future, intelligent and digital heat treatment technology will promote the heat treatment process of tungsten alloy to a higher level.

6.5 Surface coating and wear-resistant enhanced tungsten alloy rod

Tungsten alloy rods have the advantages of high density and high strength, but in high stress, friction or corrosion environment, the exposed tungsten alloy surface is prone to wear, oxidation and corrosion, affecting its service life and performance stability. Surface coating technology is a key means to improve the surface performance of tungsten alloys. It significantly enhances its wear resistance and corrosion resistance by constructing a protective layer, which is an important direction for the research and development of special tungsten alloy rods.

6.5.1 Wear and corrosion mechanism of tungsten alloy surface

- **Mechanical wear**
  During the contact and friction process of tungsten alloy, the surface material undergoes plastic deformation and fatigue cracks due to friction and shear force, leading to material peeling and abrasive grain shedding.
- **Chemical corrosion and oxidation**
  Under the action of high temperature or corrosive medium, an oxide layer or corrosion products are formed on the surface of tungsten alloy, which reduces the surface strength, is easy to peel off and aggravates the wear.
- **Fatigue wear and interface degradation**
  cyclic loading cause microcracks to propagate, the surface coating to fall off, and the protective effect to be lost.

6.5.2 Selection of surface coating materials

Coating Type	Key Features	Advantages and Applications
Hard ceramic coatings (such as TiN , CrN , Al_2O_3)	High hardness, wear resistance, high temperature resistance	Mechanical parts, molds and wear-resistant parts
Carbon-based coatings (such as diamond, carbon nitride)	Extremely high hardness, low friction coefficient	Precision instruments, cutting tools
Metal-based composite coatings (such as WC-Co, NiCr)	Good toughness, wear resistance and corrosion resistance	Highly loaded mechanical parts
Multilayer functional coating	Combination of hardness, toughness and oxidation resistance	Comprehensive performance requirements in complex service environments

6.5.3 Surface coating preparation technology

- **Physical vapor deposition (PVD)**
  uses evaporation or sputtering to deposit hard films. The coating is dense and has strong bonding force, which is suitable for high-precision tungsten alloy parts.
- **Chemical vapor deposition (CVD)**
  uses chemical reactions to form a uniform coating, which is suitable for parts with complex shapes and has excellent high temperature resistance.
- **Thermal spraying technology**
  deposits coatings by spraying molten particles. It is suitable for thick coatings and repairs, and the coating has good toughness.
- **Laser surface cladding**
  uses laser to melt powder material to achieve metallurgical bonding between the coating and the substrate, making the coating wear-resistant and corrosion-resistant.
- **Electroplating and electrochemical deposition**
  are suitable for depositing metal coatings to improve surface conductivity and corrosion resistance.

6.5.4 Improvement of tungsten alloy performance by surface coating

- **Significantly improve hardness and wear resistance**
  The coating has a higher hardness than the substrate, effectively preventing friction, wear and surface plastic deformation.
- **Enhance corrosion resistance and oxidation resistance**
  to form a stable protective film, isolate corrosive media, and delay the oxidation process.
- **Improve surface friction performance**
  , reduce friction coefficient, reduce heat generation and material loss.
- **Improve high-temperature service capability.**
  The coating has excellent high-temperature resistance and ensures structural stability in high-temperature environments.

6.5.5 Design strategy of wear-resistant enhanced tungsten alloy rod

- **The matching design of coating and substrate**
  controls the thermal expansion coefficient of coating to match that of substrate, avoiding cracking and shedding of coating caused by thermal stress under high temperature.
- **The multi-layer composite coating technology**
  uses a hard layer and a tough layer to combine wear resistance and impact resistance.
- **Surface roughness optimization:**
  Detailed surface treatment before coating to improve coating adhesion.
- **Coating thickness and uniformity control**
  Rationally design coating thickness to prevent performance degradation caused by uneven thickness.

6.5.6 Application Cases

- **tungsten alloy coating of**
  aerospace engine turbine blades adopts TiN / Al_2O_3 composite coating, which improves the wear resistance by 50% and significantly extends the blade life.
- **Military armor-piercing core coating technology:**
  hard carbide coating enhances the surface hardness of the core, improves penetration ability and wear resistance.
- **on the surface of electronic heat dissipation components**
  improves thermal conductivity and corrosion resistance, ensuring long-term and stable operation of the equipment.

6.5.7 Development Trends and Challenges

- **Development of Nanostructured Coatings**
  Nanocrystalline coatings are denser, have both hardness and toughness, and have better wear resistance.
- **Intelligent coating functional integration**
  combines self-repairing, antibacterial, anti-corrosion and other functions to expand the application field.
- **Environmentally friendly coating technology and**
  green preparation process reduce environmental impact and improve industry sustainability.
- **The interface engineering optimization between coating and substrate**
  improves the interface bonding strength and prevents coating shedding and fatigue failure.

summary
Surface coating technology provides tungsten alloy rods with efficient anti-wear and anti-corrosion protection, greatly improving their service life and performance stability in extreme environments. Through the continuous development of advanced coating materials and preparation processes,

wear-resistant and enhanced tungsten alloy rods will play a more critical role in aerospace, military industry, and high-end manufacturing. In the future, the diversification and intelligence of coating functions will become a new direction for technological development.

6.6 Functional tungsten alloy rod: electrical conductivity, thermal conductivity, anti-magnetic

As a high-density, high-performance material, tungsten alloy rods not only have excellent mechanical properties and high-temperature stability, but also have the increasing demand for multifunctional materials in modern industry and high-tech fields. Functional tungsten alloy rods such as electrical conductivity, thermal conductivity and anti-magnetic properties have gradually become the focus of research and development. Through material design and process control, the functionalization of tungsten alloy rods can be realized, its application areas can be expanded, and its overall performance can be improved.

Design and application of conductive tungsten alloy rod

- **Design principles**
  - Improve the electrical conductivity of the alloy while maintaining good mechanical properties;
  - Optimize the types and contents of alloy elements to reduce the obstacles to electron migration;
  - Control the microstructure and reduce the impact of grain boundaries and defects on resistance.
- **Common alloying elements**
  - Copper (Cu) is an excellent conductive element and is often used to improve the conductivity of tungsten alloys.
  - The appropriate addition of elements such as silver (Ag) and nickel (Ni) helps to balance conductivity and mechanical properties.
- **Application Areas**
  - Electronic packaging materials;
  - Electrode materials in vacuum electronic devices;
  - Heat dissipation support for high frequency circuits.
- **Performance characteristics**
  - The resistivity can be reduced to micro-ohm-cm level;
  - At the same time, it maintains high strength and thermal stability;
  - Good machinability and dimensional stability.

Design and application of thermal conductive tungsten alloy rod

- **Design Strategy**

  - Taking advantage of the high thermal conductivity of tungsten itself, combined with high thermal conductivity alloy elements to improve the overall thermal conductivity;
  - Optimize microstructure and reduce thermal resistance interface;
  - Apply grain refinement and defect control processes to reduce scattering effects.
- **Typical alloy systems**
  - Tungsten-copper (W-Cu) composite alloys are widely used in high thermal conductivity applications;
  - Improving thermal conductivity through microalloying and nanostructure design.
- **Application Scenario**
  - Heat dissipation components for high-power electronic devices;
  - Aircraft engine combustion chambers and heat exchangers;
  - Thermal management components in lasers and nuclear reactors .
- **Performance Advantages**
  - The thermal conductivity is significantly better than pure tungsten, reaching more than 200 W/(m·K);
  - It combines high density, high strength and excellent thermal stability.

Design and application of anti-magnetic tungsten alloy rod

- **Design goals**
  - Make tungsten alloy non-magnetic or weakly magnetic in a strong magnetic field environment;
  - Prevent magnetic field interference and ensure the normal operation of the equipment.
- **Ingredient Control**
  - Reduce the content of ferromagnetic elements such as iron (Fe), cobalt (Co), and nickel (Ni);
  - Add non-magnetic alloy elements such as chromium (Cr) and manganese (Mn);
  - Utilize solid solution strengthening and second phase control to reduce magnetic response.
- **Application Areas**
  - Magnetic resonance imaging (MRI) equipment;
  - High-precision magnetic field measuring instruments;
  - Particle accelerator and nuclear reactor components.
- **Performance**
  - The magnetic permeability is close to 1 (the magnetic permeability of vacuum);
  - Maintain good mechanical and high temperature resistance properties;
  - Excellent radiation and corrosion resistance.

Preparation technology of functional tungsten alloy rod

- **Precision powder metallurgy technology**
  controls powder purity and particle size to ensure uniform composition and reduce defects.
- **Advanced heat treatment technology**
  regulates microstructure and optimizes functional performance.
- **Surface modification technology**
  improves surface functions, such as conductive coating, wear-resistant coating, etc.
- **Additive manufacturing**
  enables complex structure and functional gradient design to meet multi-functional needs.

6.6.5 Future Development Trends

- **The multifunctional integrated design**
  takes into account multiple functions such as electrical conductivity, thermal conductivity, and anti-magnetic properties to meet complex application requirements.
- **Nanostructure manipulation**
  uses nanotechnology to further improve performance and enhance stability.
- **Smart Material Development Develop smart**
  tungsten alloy materials that respond to environmental changes and achieve adaptive performance adjustments.
- **Green and environmentally friendly preparation technology**
  promotes low-energy consumption and low-pollution preparation processes and promotes sustainable development.

summary

Functional tungsten alloy rods have successfully achieved multiple special functions such as electrical conductivity, thermal conductivity and anti-magnetic properties through reasonable composition design and process optimization, greatly expanding the application space of tungsten alloy in high-tech fields. With the continuous advancement of material science and manufacturing technology, functional tungsten alloy rods will play an increasingly important role in many cutting-edge fields such as electronics, aviation, and medical treatment.

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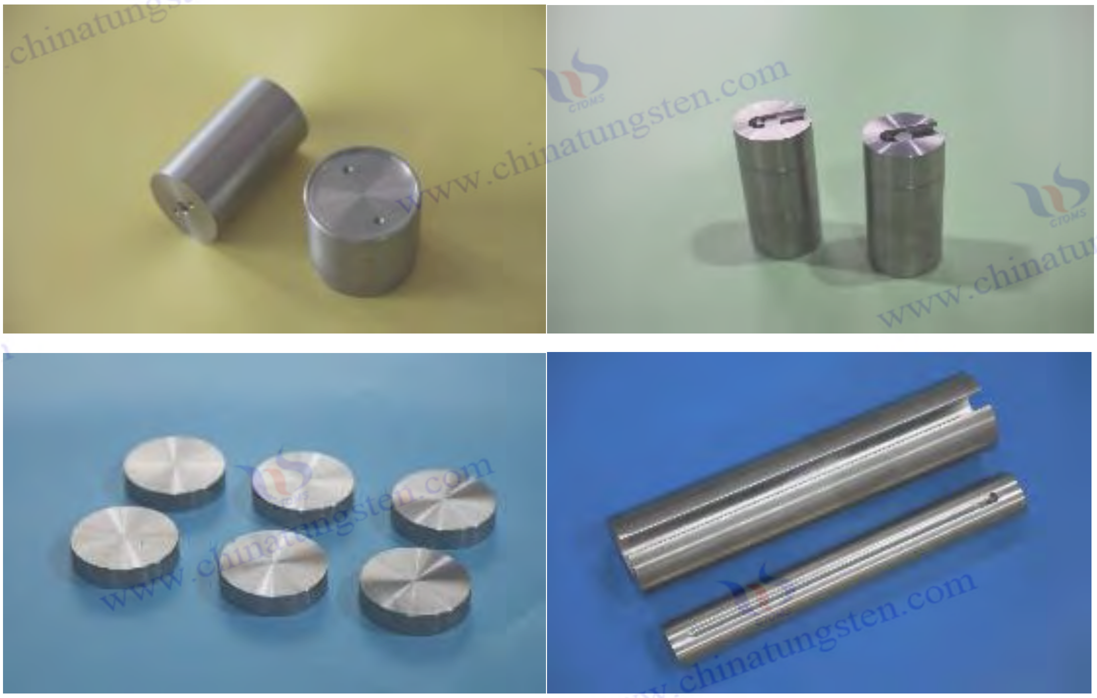

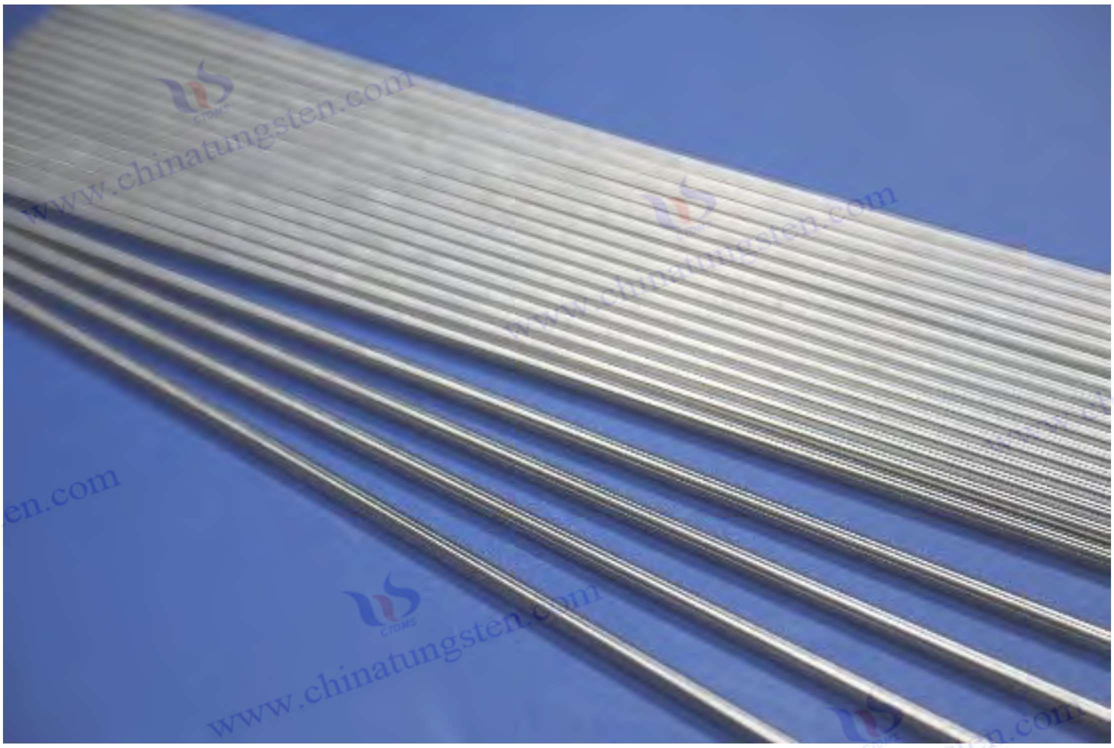

Chapter 7 Compliance System for Tungsten Alloy Rods

7.1 Chinese national/industry standards (GB/T, YS/T)

As an important high-performance material, tungsten alloy rods must meet strict quality and performance standards in industrial production and application. China's national standard (GB/T) and industry standard (YS/T) system provide a regulatory basis for the manufacture, testing and application of tungsten alloy rods, ensuring stable product quality and healthy development of the industry.

7.1.1 Overview of China’s Standards System

- **National Standard (GB/T)**
  National standards are issued by the State Administration for Market Regulation and the National Standardization Administration, covering material properties, testing methods, technical requirements, etc., and are the basis for enterprise production and quality inspection. For example: GB/T 23789-2017 "High Specific Gravity Tungsten Alloy Materials" and GB/T 20211-2006 "Tungsten Alloy Rods".
- **Industry standards (YS/T)**
  are formulated by relevant industry authorities, which refine standard requirements according to industry characteristics and are applicable to technical specifications and evaluations within the industry. Example: YS/T 531-2014 "General Technical Conditions for Tungsten Alloy and Tungsten-Copper Alloy Materials".

- **Local standards and enterprise standards**
  Some regions and enterprises formulate supplementary standards based on actual needs to refine management and enhance competitiveness.

7.1.2 Main national standards (GB/T)

Standard No.	Standard Name	Main content and application
GB/T 23789-2017	High specific gravity tungsten alloy material	Tungsten alloy classification, technical requirements, performance indicators, etc.
GB/T 20211-2006	Tungsten Alloy Rod	Chemical composition and mechanical properties testing methods of tungsten alloy rods
GB/T 13298-2009	Tungsten Alloy Material Mechanical Properties Test Method	Standardize mechanical properties test standards and test methods
GB/T 19290-2003	Tungsten Alloy Material Density Measurement Method	Determination and Error Analysis of Tungsten Alloy Density

7.1.3 Main industry standards (YS/T)

Standard No.	Standard Name	Scope of application and characteristics
YS/T 531-2014	General technical requirements for tungsten alloy and tungsten-copper alloy materials	Detailed specification of technical requirements for tungsten alloy and tungsten copper alloy
YS/T 155-2012	High Density Tungsten Alloy Products	Manufacturing process and performance control of tungsten alloy products
YS/T 786-2016	Tungsten Alloy Mechanical Properties Test Method	Mechanical properties test standards to ensure accurate test data

7.1.4 Key points of the standard

- **chemical composition control**
  standards clearly define the content range and impurity limits of elements such as tungsten, nickel, iron, and copper to ensure stable material performance.
- **The mechanical performance indicators**
  specify key performance indicators such as tensile strength, yield strength, elongation, hardness, etc. to meet different application requirements.
- **Dimensional accuracy and surface quality**
  put forward specific requirements for the dimensional tolerance, surface roughness and defect limit of tungsten alloy rods.
- **Inspection and testing methods**
  include density measurement, metallographic analysis, mechanical property testing and non-destructive testing technical standards to ensure that product quality is controllable.

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7.1.5 Standard implementation and supervision management

- **Responsibilities of Manufacturing Enterprises**
  Enterprises should strictly follow national and industry standards in production and inspection to ensure that products meet specifications.
- **quality supervision**
  departments of the quality supervision agencies are responsible for supervising the implementation of standards and random inspections of product quality.
- **Certification and testing agencies**
  Third-party certification agencies provide quality certification for companies and products to enhance market acceptance.

7.1.6 Standard Update and Development Trend

- **Adapting to high-end application needs,**
  with the upgrading of technology in aerospace, nuclear industry and other fields, standards are constantly being refined to improve performance indicators and detection accuracy.
- **The integration of environmental and safety standards**
  strengthens environmental protection and safety performance specifications, in line with green manufacturing and international compliance requirements .
- **International integration and coordination**
  promote the integration with ISO and other international standards, and promote the internationalization of China's tungsten alloy rod industry .

summary

China's tungsten alloy rod national standard (GB/T) and industry standard (YS/T) system provide comprehensive technical support and quality assurance for the production and application of tungsten alloy rods . With the advancement of technology and changes in market demand, the standard system continues to improve, helping China's tungsten alloy rod industry to steadily move towards high-quality development and international competition.

7.2 American Standard System (ASTM, MIL)

As an important country in the world of advanced manufacturing and material technology, the United States has a wide range of influence on the production, testing and application of tungsten alloy rods. ASTM (American Society for Testing and Materials) standards and MIL (US Military Standards) are the core of US tungsten alloy material specifications, ensuring that product performance meets the strict requirements of the civilian and military fields.

7.2.1 Overview of ASTM Standard System

- As an internationally renowned standards-setting organization, ASTM **International is responsible for developing a series of standards covering material properties, test methods and quality control to promote the development of materials science and industrial applications.**

- **ASTM standards related to**
tungsten alloys ASTM standards systematically regulate the chemical composition, mechanical properties, testing methods and quality assessment of tungsten alloys.

7.2.2 Main ASTM standards and applications

Standard No.	Standard Name	Contents
ASTM B777	Specifications of tungsten and tungsten alloy powders	Powder quality requirements and inspection methods
ASTM B777-18	Tungsten Alloy Density and Mechanical Properties Test Standards	Tungsten alloy density, tensile strength and hardness test
ASTM E8/E8M	Metal material tensile test standard	Standardize the tensile test procedure of tungsten alloy
ASTM B765	Chemical Analysis Methods of Tungsten Alloy Materials	Spectral Analysis and Detection Methods of Tungsten Alloy Composition
ASTM E112	Grain size determination standard	for tungsten alloy microstructure

7.2.3 Overview of the MIL (Military Standard) System

- **MIL standard system is**
a military standard formulated by the U.S. Department of Defense, which puts forward extremely high performance, reliability and safety requirements for military products. As one of the key materials, tungsten alloy, MIL standard covers material preparation, performance indicators and quality control.
- **The characteristics of MIL standards**
focus on the service performance and environmental adaptability of materials. The specifications are strict and operational, and are widely used in military ammunition, aerospace and nuclear energy equipment.

7.2.4 Typical MIL standards and their applications

Standard No.	Standard Name	Main content

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MIL-T-21005	tungsten alloy rods and products	Composition, mechanical properties and dimensional specifications of tungsten alloy rods
MIL-STD-810	Environmental Engineering Considerations and Experimental Test Standards	tungsten alloy materials in harsh environments
MIL-STD-883	Microelectronic Device Material Testing Methods	Tungsten Alloys in Microelectronic Packaging

7.2.5 Key points of the standard

- **Strict chemical composition and impurity control**
  MIL standards have strict limits on alloy composition and impurity content to ensure that material properties are consistent and meet the high standards of military applications.
- **Comprehensive mechanical properties tests**
  include tensile strength, yield strength, elongation, hardness and fatigue performance to ensure the reliability of tungsten alloy rods under extreme conditions.
- **Environmental adaptability testing:**
  Develop detailed testing plans for high temperature, low temperature, humidity, vibration, impact and other environments.
- **The quality management and traceability system**
  emphasizes production process control and product traceability to ensure the full life cycle management of material quality.

7.2.6 Advantages and influence of the US standard system

- **High International Recognition**
  ASTM and MIL standards are widely recognized and adopted worldwide, promoting international trade and technical cooperation of tungsten alloy rods.
- **Promote technological innovation**
  standards, promote the continuous upgrading of material performance and testing technology, and drive industrial technological progress.
- **Ensure the safety of critical applications**
  . Strict standards are used to ensure the safe and stable use of tungsten alloy materials in the aerospace, military and nuclear industries.

summary

The ASTM and MIL standard systems in the United States provide a perfect framework for the quality control and performance assurance of tungsten alloy rods, meeting the diverse needs from civilian to military applications. Its scientific and rigorous standard content and wide industry applicability have played a positive role in promoting the development and application of tungsten alloy materials worldwide.

7.3 EU and ISO International Standards

the increasing frequency of global tungsten alloy material trade and technical exchanges, the relevant standards formulated by the European Union (EU) and the International Organization for Standardization (ISO) have become an important force in promoting the internationalization of the tungsten alloy rod industry and unifying technical specifications. EU standards emphasize environmental protection, safety and compliance , while ISO standards focus on the international unification of material properties and test methods, providing an authoritative technical framework for tungsten alloy rods in the global market .

7.3.1 Overview of the EU Standards System

- **The EU standardization bodies**
  are mainly composed of the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI).
  Tungsten alloy rod related standards are usually formulated by CEN, focusing on safety, environment and performance requirements.
- **EU Compliance Framework Tungsten**
  alloy materials must comply with EU environmental regulations, such as RoHS (Restriction of Hazardous Substances Directive), REACH (Registration, Evaluation, Authorization and Restriction of Chemicals), etc., to ensure product safety and environmental compliance.

7.3.2 Main EU-related standards and regulations

Standard/regulation name	Main content	Scope of application
EN 12502 series	Specifications and test methods for tungsten and tungsten alloy materials	Tungsten Alloy Material Performance and Quality Testing
RoHS Directive (2011/65/EU)	Restriction of the use of hazardous substances in electrical and electronic equipment	Tungsten alloy electronic components and related products
REACH Regulation (EC 1907/2006)	Chemical Registration and Safety Management Requirements	Environmental Compliance in Tungsten Alloy Production and Supply Chain
CE Marking	Product Safety and Compliance Certification Marks	tungsten alloy products to enter the EU market

7.3.3 Overview of ISO International Standards System

- **Introduction to ISO Organization**
  The International Organization for Standardization (ISO) is an authoritative organization that develops global unified standards, covering many aspects such as material properties, test methods, quality management, etc.
- **ISO standards related to**
  tungsten alloys ISO standards focus on regulating the performance indicators, test methods

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and quality management of tungsten alloy materials, providing a unified basis for international trade and technical cooperation.

7.3.4 Main ISO standards and their applications

Standard No.	Standard Name	Main content
ISO 9001	Quality management system requirements	Quality Management System of Tungsten Alloy Rod Manufacturing Enterprises
ISO 16143	Metal Powder Material - Powder Metallurgy Tungsten Alloy	Technical Specifications and Test Methods of Tungsten Alloy Powder
ISO 4967	Methods for determination of carbon and sulfur	Chemical composition testing of tungsten alloy materials
ISO 6892	Tensile test methods for metal materials	Tungsten Alloy Mechanical Properties Tensile Test Standard
ISO 6507	Metal Hardness Test—Vickers Hardness	International Standards for Tungsten Alloy Hardness Testing

7.3.5 Key points of the standard

- **Environmental and Safety Compliance**
  EU standards strictly restrict the use of hazardous substances, ensuring that tungsten alloy materials meet environmental protection requirements and promote green manufacturing.
- **International Unification of Performance Testing**
  ISO standards unify the physical and mechanical performance testing methods of tungsten alloys to ensure the comparability of performance data of products across countries.
- **quality management system construction**
  promotes tungsten alloy manufacturers to establish a sound quality management system and improve production and management levels.
- **technical exchanges and market access**
  reduce international trade barriers and facilitate tungsten alloy rod products to enter the global market.

7.3.6 Synergy between EU and ISO standards

- EU standards are often formulated with reference to ISO international standards, promoting global consistency in technical standards.
- ISO standards provide companies with a foundation for quality management and technical specifications, supporting compliance certification in accordance with EU regulations .
- The two sides jointly promote the technological upgrading and green development of the tungsten alloy industry and promote international cooperation.

summary

The EU and ISO standard systems provide a comprehensive international regulatory framework for the tungsten alloy rod industry , covering multiple dimensions such as performance, testing, environmental protection and quality management. Compliance with these standards not only helps to ensure product quality and safety, but also promotes the international competitiveness and market expansion of Chinese tungsten alloy companies. In the future, with the continuous improvement and updating of international standards, the tungsten alloy rod industry will usher in a higher level of standardization and international development.

7.4 Environmental protection and material safety certification (RoHS, REACH, MSDS)

As the world pays more attention to environmental protection and occupational health and safety, the production and application of tungsten alloy rods must strictly comply with relevant environmental laws and regulations and material safety standards. RoHS, REACH and MSDS certification have become a prerequisite for tungsten alloy companies to enter the international market, especially the EU market. These certifications not only ensure the environmental compliance of materials , but also ensure the safety of users and the environment.

7.4.1 RoHS Directive (Restriction of Hazardous Substances Directive)

- **Directive Introduction**
  The RoHS (Restriction of Hazardous Substances) directive was issued by the European Union in 2003 to restrict the use of hazardous substances in electrical and electronic equipment and to protect the environment and human health.
- **The main restricted substances**
  include lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr(VI)), polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE).
- **Impact on tungsten alloy rods**
  If tungsten alloy materials are used in electronic and electrical products, it is necessary to ensure that the content of the above-mentioned harmful substances meets the RoHS limit to avoid exceeding the limit and affecting market access.
- **Testing and Compliance Companies**
  are required to conduct strict material composition testing and provide RoHS compliance declarations and test reports.

7.4.2 REACH Regulation (Registration, Evaluation, Authorization and Restriction of Chemicals)

- **Regulatory Background**
  REACH is a comprehensive chemical management regulation implemented by the European Union in 2007, requiring manufacturers and importers to register and evaluate the safety of chemicals.

- **Registration Obligations of Tungsten Alloy Materials** Tungsten alloy manufacturers must register their products with the European Chemicals Agency (ECHA) and submit safety data and risk assessments.
- **Material Evaluation and Restriction**
  If tungsten and its compounds are included in the list of substances of very high concern (SVHC), they must be specially managed and restricted.
- **Supply chain responsibility**
  requires companies to be transparent about chemical information in the supply chain and ensure that downstream users are aware of material safety information.

7.4.3 MSDS (Material Safety Data Sheet)

- **Definition and Function**
  MSDS is a material safety data sheet that provides the chemical properties, health hazards, protective measures and emergency treatment guidelines of tungsten alloy rods.
- **The content is required**
  to include information on physical and chemical properties, hazard identification, storage and transportation, exposure control and personal protection.
- **Enterprise Obligations**
  Production and supply enterprises must prepare and provide MSDS that complies with international standards to ensure safe use.

7.4.4 The significance of environmental protection and safety certification

- **Protect the environment and health**
  by controlling the emission of hazardous substances and reducing environmental pollution and occupational health risks.
- **Promote market access**
  Through RoHS and REACH certification, tungsten alloy rod products are recognized by the EU and major global markets.
- **Improving corporate competitiveness**
  Environmental compliance is an important manifestation of corporate social responsibility and brand reputation.
- **Support sustainable development,**
  promote green manufacturing and circular economy, and promote the healthy development of the industry.

7.4.5 Response strategies of tungsten alloy enterprises

- **Strengthen material composition management**
  and strictly control the content of harmful substances in raw material procurement and production processes.

- **Improve the testing and monitoring system,**
  establish internal testing capabilities, and cooperate with third-party certification agencies to carry out compliance testing .
- **Actively apply for relevant certifications**
  to obtain RoHS, REACH and other certification certificates to meet customer and market needs.
- **Improve information transparency**
  and provide complete MSDS and technical support to ensure safe use by customers.

Summary
Environmental protection and material safety certification is an important pass for the tungsten alloy rod industry to enter the international market. By strictly complying with RoHS and REACH regulations and improving MSDS management, enterprises not only ensure the safety and compliance of products , but also lay a solid foundation for sustainable development and global competition. In the future, with the continuous improvement of environmental protection laws and regulations, tungsten alloy rod companies need to continue to improve their environmental management level to adapt to higher market and social requirements.

7.5 Quality system requirements in the aviation, military and medical fields

As a key high-performance material, tungsten alloy rods are used in high-end fields such as aerospace, military equipment and medical equipment, which places extremely high demands on the quality system. Relevant industries usually adopt strict quality management systems and certification standards to ensure the safety, reliability and consistency of materials and meet the service requirements under extreme working conditions.

7.5.1 Quality system requirements in the aerospace sector

- **Industry Standards and Certifications**
  - AS9100: Aerospace quality management system standard, based on ISO 9001 and adding aerospace-specific requirements;
  - NADCAP: Aerospace special process certification, covering key links such as heat treatment and non-destructive testing.
- **Key Quality Control Points**
  - Batch traceability and consistency of materials;
  - Strict physical and chemical performance tests;
  - High-precision size control and surface quality requirements.
- **Quality Management Measures**
  - Implement risk management and process controls;
  - Use advanced testing technology (such as X-ray, CT scan) for non-destructive testing;
  - Conduct supply chain audits and on-site reviews regularly.

7.5.2 Quality system requirements in the military industry

- **Military quality standards**
  - MIL-Q-9858A: Military quality assurance system;
  - MIL-STD-105E: Military sampling inspection standard;
  - MIL-STD-1916: Military process control standard.
- **Performance and reliability requirements**
  - Meet performance specifications for extreme temperature, shock and vibration environments;
  - High purity and low impurity content ensure the service life of the material;
  - Strict defect rate control and defect repair standards.
- **Quality Assurance Measures**
  - Complete product traceability system;
  - Use advanced measurement and testing equipment;
  - Emphasize employee training and implementation of process specifications.

7.5.3 Quality system requirements in the medical field

- **Medical device quality standards**
  - ISO 13485: Quality management system standard for medical devices;
  - FDA 21 CFR Part 820: U.S. Food and Drug Administration quality regulations for medical devices.
- **Safety and biocompatibility**
  - Tungsten alloy materials must meet biocompatibility requirements to avoid toxicity and allergic reactions;
  - Strict cleaning and sterilization standards;
  - Ensure the stability and safety of materials in medical environments such as radiotherapy.
- **Quality Management Measures**
  - Establish a comprehensive risk management system (ISO 14971);
  - Documented design control and change management processes;
  - Regular internal audits and external certifications.

7.5.4 Common quality system implementation points

- **System Certification and Continuous Improvement**
  Enterprises must pass the quality management system certification of authoritative organizations in related fields and continuously improve and optimize the quality control process.

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- **Strict supply chain management**
  implements quality control and tracking throughout the entire process from raw material procurement to final product delivery.
- **Data-driven quality monitoring**
  uses big data and information technology to conduct real-time monitoring and early warning of the production process.
- **Talent cultivation and cultural construction**
  focus on the cultivation of quality awareness and create a quality management culture with the participation of all employees.

summary

The aviation, military and medical fields have set extremely high standards and strict management requirements for the quality system of tungsten alloy rods. Enterprises need to establish a complete quality management system based on the characteristics of the industry to ensure the reliability and safety of materials under extreme working conditions. This is not only the basis for meeting customer needs, but also the key to enhancing corporate competitiveness and promoting high-quality development of the industry.

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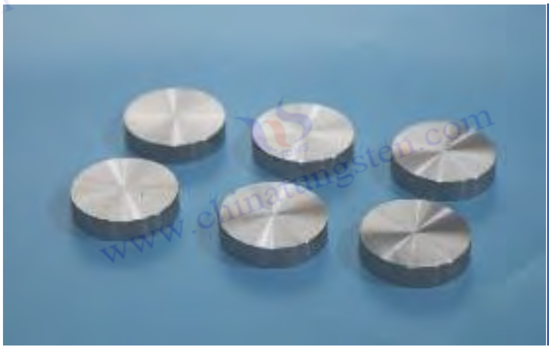
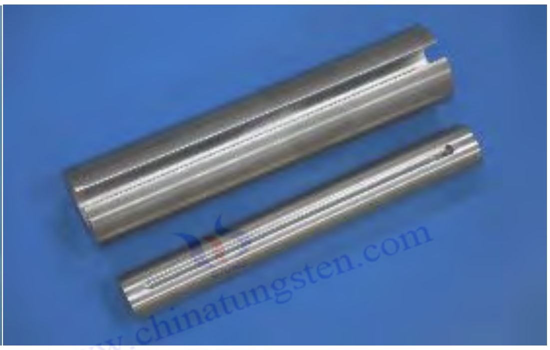

Chapter 8 Packaging, Storage and Transportation of Tungsten Alloy Rods

8.1 Packaging method and protective measures (vacuum packaging, desiccant)

Tungsten alloy rods have high density, high hardness and special application requirements, so packaging and protective measures are particularly important. Reasonable packaging design can not only protect the product from mechanical damage, corrosion and environmental impact, but also ensure safety and integrity during transportation.

8.1.1 Packaging

- **Vacuum packaging**
  - Use vacuum technology to extract the air in the package to reduce the oxidation and corrosion of the tungsten alloy surface by oxygen and moisture;
  - Suitable for long-term storage and export transportation, especially in environments with high humidity or large temperature differences;
  - Vacuum packaging bags are generally made of multi-layer composite materials with good air tightness and mechanical strength.
- **Anti-rust paper and plastic film packaging**
  - Wrap the surface of the tungsten alloy rod with anti-rust paper to form a physical isolation layer to prevent the intrusion of water vapor and corrosive media;
  - The outer layer is then wrapped with plastic film to prevent mechanical scratches and dust pollution;

- Suitable for short-term storage and transportation under normal environmental conditions.

- **Wooden box and wooden pallet packaging**
  - After primary packaging, the tungsten alloy rods are placed in sturdy wooden boxes to prevent impact and vibration during transportation;
  - The wooden box is equipped with cushioning materials, such as foam or pearl cotton, to further protect the product;
  - Wooden pallets are easy to carry by forklifts, improving logistics efficiency.
- **Metal drum or steel cylinder packaging**
  - tungsten alloy rods with special specifications or high value , metal barrels or steel cylinders are used for packaging to improve the protection strength;
  - At the same time, it is easy to seal and protect, which is conducive to ocean transportation.

8.1.2 Protective measures

- **Use of desiccant**
  - Place desiccant (such as silica gel, molecular sieve) inside the package to effectively absorb moisture in the packaging space and prevent oxidation caused by moisture;
  - The amount of desiccant should be reasonably configured according to the packaging volume and the humidity of the transportation environment;
  - Replace the desiccant regularly to ensure the dryness of the packaging environment.
- **Anti-corrosion coating or oil film**
  - Apply anti-rust oil or special anti-corrosion coating on the surface of tungsten alloy rod to provide chemical protection layer;
  - Prevent moisture and salt spray environments from corroding the material surface.
- **Shockproof buffer design**
  - Design a multi-layer buffer structure inside the packaging box to reduce mechanical vibration and impact during transportation;
  - tungsten alloy rod is wrapped with shock-absorbing material to prevent surface scratches and deformation.
- **Sealing performance guaranteed**
  - The packaging should have good sealing performance to prevent air and dust from entering;
  - Vacuum or nitrogen filling packaging can further improve the sealing effect.

8.1.3 Key points of packaging design

- **Customize the packaging structure according to the product size and weight.**
  Tungsten alloy rods are heavy, so the packaging materials and structures must have sufficient bearing capacity to prevent damage during transportation.
- **The labels are clear and complete.**
  The product specifications, weight, precautions and transportation direction are marked on the outside of the packaging box to facilitate logistics and warehousing management.
- **Environmentally friendly material selection**
  gives priority to environmentally friendly and recyclable materials, which comply with green manufacturing and environmental regulations.

summary

Scientific and reasonable packaging methods and protective measures are the key to ensuring the quality and safe transportation of tungsten alloy rods. Through vacuum packaging, desiccant use, anti-corrosion coating and buffer design, oxidation, corrosion and mechanical damage can be effectively prevented, providing solid protection for the storage and transportation of tungsten alloy rods. With the development of logistics technology and environmental protection concepts, tungsten alloy rod packaging solutions will continue to be optimized to help the green and sustainable development of the industry.

8.2 Storage conditions and precautions (temperature and humidity control, corrosion prevention)

During the storage process, tungsten alloy rods are greatly affected by the ambient temperature, humidity and chemical media. Improper storage conditions may cause surface oxidation and corrosion of the material, and even internal performance degradation. Therefore, scientific and reasonable storage management is essential to maintain the quality of tungsten alloy rods.

8.2.1 Temperature and humidity control

- **Temperature requirements**
  - The storage environment should maintain a constant and suitable temperature, usually 15℃~25℃ is recommended, and avoid drastic temperature changes;
  - High temperature may accelerate the oxidation reaction on the surface of the material, affecting the surface finish and mechanical properties;
  - If low temperature is accompanied by increased humidity, condensation water is likely to form, causing corrosion.
- **Humidity requirements**
  - The relative humidity should be controlled between 40% and 60% to prevent excessive humidity from causing rust on the metal surface;
  - Too low humidity will cause the desiccant to fail quickly and need to be replaced in time;

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  - Equip air dehumidification equipment, such as a dehumidifier, to maintain a dry environment.
- **Environmental Monitoring**
  - Storage warehouses should be equipped with temperature and humidity monitoring devices to monitor environmental parameters in real time;
  - Take timely adjustment measures when abnormalities occur to ensure a stable environment.

8.2.2 Anti-corrosion measures

- **Rust Inhibitors and Coating Protection**
  - Coat the surface of the tungsten alloy rod with anti-rust grease or special anti-corrosion coating to form an isolation layer to prevent direct contact between oxygen and moisture;
  - Check the integrity of the coating regularly and repair or re-coat if any damage is found.
- **Isolation packaging**
  - Use anti-rust paper or plastic film to wrap the product to reduce direct air contact;
  - Place desiccant inside the package to absorb moisture and prevent the formation of a humid environment inside.
- **Warehouse environment management**
  - Avoid direct contact of tungsten alloy rods with wet ground and store them overhead;
  - Prevent chemical corrosive gases (such as sulfides and chlorides) from invading the warehouse environment;
  - Ventilate regularly to avoid accumulation of harmful gases in confined spaces.

8.2.3 Storage Management Notes

- **Stacking method**
  - Tungsten alloy rods are heavy and should be stacked properly to avoid deformation caused by high stacking pressure ;
  - Stacked in batches according to specifications for easy management and retrieval.
- **Protection logo**
  - The storage area should be clearly marked with safety reminders such as "moisture-proof, fire-proof, and pressure-proof";
  - Critical materials should have dedicated storage areas to avoid mixing and cross contamination.
- **Regular inspection and maintenance**
  - Establish a storage inspection system to check packaging integrity, rust prevention and environmental parameters;

- Any abnormal situations found should be dealt with promptly to prevent quality problems from expanding.

summary

Reasonable temperature and humidity control and scientific anti-corrosion measures are the basis for ensuring the storage quality of tungsten alloy rods. By maintaining appropriate environmental parameters, combined with effective packaging protection and storage management, the product life can be maximized to ensure that the material maintains excellent physical and mechanical properties before use. Enterprises should pay attention to the storage link, implement management systems, and ensure the safe and stable storage of tungsten alloy rods .

8.3 International Transport Regulations and Dangerous Goods Declaration Guidelines

As a high-density metal material, the international transportation of tungsten alloy rods involves the regulations and customs requirements of many countries. It is necessary to strictly abide by the relevant regulations to ensure transportation safety, compliance and smooth customs clearance. Especially when it comes to dangerous goods declaration, companies should accurately judge the product properties and prepare complete transportation documents.

8.3.1 Overview of International Transport Regulations

- **International Maritime Dangerous Goods Code (IMDG Code)**
  The International Maritime Dangerous Goods Code, established by the International Maritime Organization (IMO), regulates the classification, packaging, labeling and declaration of dangerous goods during maritime transport.
- **The International Air Transport Association (IATA) Dangerous Goods Regulations**
  regulate the requirements for dangerous goods transported by air, covering packaging, declaration, labelling and handling procedures.
- **The United Nations Recommendations on the Transport of Dangerous Goods (UN Recommendations)**
  unify global dangerous goods classification and labeling standards and are the basis for dangerous goods transportation regulations in various countries.
- **Customs and transportation departments of various countries**
  have specific requirements for the transportation of tungsten alloy rods in different countries, and the relevant laws of the importing and exporting countries must be followed.

8.3.2 Transportation Classification and Dangerous Goods Declaration of Tungsten Alloy Rods

- **tungsten alloy rod a dangerous item?**
  - Generally speaking, pure tungsten alloy rods are not dangerous goods and do not have special dangerous chemical properties.

- o However, if the surface of the tungsten alloy rod is coated with flammable grease or contains other hazardous chemicals, it must be declared according to the corresponding category.

- **Application Process**
  - o Prepare product data sheets and safety data sheets (MSDS);
  - o Fill out the dangerous goods declaration form according to the mode of transportation, and specify the packaging category and label;
  - o Provide packaging and labeling that meet standards;
  - o Declare to the carrier and relevant regulatory authorities and obtain approval.

8.3.3 Packaging and labeling requirements

- **Packaging that meets transportation standards**
  - o The packaging materials must meet the strength and sealing requirements of IMDG and IATA;
  - o Make sure the packaging can withstand vibration, extrusion and climate change during transportation.
- **Dangerous Goods Signs and Labels**
  - o Non-dangerous goods do not need special labeling, but they should be marked with weight, size and fragility.
  - o If it contains dangerous substances, the corresponding dangerous goods labels and transportation marks must be affixed.
- **Dangerous goods packaging code**
  - o The packaging box should have UN number, packaging type and performance test mark.

8.3.4 Precautions for international transportation

- **Accurate classification**
  - o Carefully verify the properties of the product and its associated materials to avoid misreporting that may lead to shipping delays or fines.
- **File Complete**
  - o Prepare complete shipping documents, including commercial invoice, packing list, dangerous goods declaration form, safety data sheet and relevant licenses.
- **Choose a compliant carrier**
  - o Choose an experienced logistics and customs broker to ensure that the transportation plan complies with regulatory requirements.
- **Shipping Insurance**
  - o Purchase appropriate cargo transportation insurance to prevent transportation risks.
- **Emergency Plan**
  - o Develop emergency response plans for transportation accidents and equip with necessary emergency supplies.

summary

tungsten alloy rods involves complex regulations and procedures. Accurately understanding the transportation classification and declaration requirements and using standard packaging and labeling are the keys to ensuring transportation safety and smooth customs clearance. Enterprises should establish a complete transportation compliance system , improve management level, reduce transportation risks, and ensure the smooth global circulation of tungsten alloy rod products .

8.4 Customs Supervision and License Requirements for Export of Tungsten Alloy Rods

As a strategic metal material, the export of tungsten alloy rods is strictly regulated by many governments. Exporting companies must abide by relevant national laws and regulations, apply for necessary export licenses, fulfill customs declaration obligations, and ensure that the products are exported smoothly and meet the requirements of the importing country.

8.4.1 Overview of customs supervision policy

- **Strategic Resource Management**
  Since tungsten is a rare metal, the country usually lists it as a strategic resource that requires key management, and implements quota management and licensing system for its export.
- **Customs declaration requirements:**
  The export of tungsten alloy rods must be declared in accordance with customs regulations, providing accurate commodity code (HS code), specification model, quantity and value and other information.
- **Export restrictions and controls**
  Some countries and regions have special restrictions on the export of tungsten alloys, such as technical sensitivity control, anti-dumping investigations, etc. Enterprises need to understand the relevant policies in advance.

8.4.2 Export License Application Process

- **license**
  is generally issued by the national commerce department or metal material management department.
- **Application Materials**
  - Business license and qualification certificate of the enterprise;
  - Product test reports and quality certification documents;
  - Contract and order proof;
  - Customs declaration and related shipping documents.
- **Approval Process**

1. Submit application materials to the competent authority;
2. Relevant departments review product quality and compliance ;

3. After approval, the export license will be issued;
4. Enterprises shall go through customs export formalities with the license.

- **Validity Period and Renewal**
  Export licenses generally have validity period limits, and companies must renew them on time to ensure continued exports.

8.4.3 Key points of customs declaration and supervision

- **Accurate HS Coding**
  Tungsten alloy rods should use the internationally accepted Harmonized System (HS) coding to ensure accurate customs classification and taxation.
- **Customs clearance documents**
  include invoices, packing lists, export licenses, contracts, shipping documents and certificates of origin, etc., to ensure that all documents are complete.
- **Customs inspection and random inspection**
  Tungsten alloy rods may be inspected when exported, and enterprises need to cooperate in providing samples and test reports.
- **Tax Policy**
  Understand the export tax rebate policy and related benefits, and plan the export process reasonably.

8.4.4 Precautions and risk prevention and control

- **Compliance risks avoid illegal activities such as false** declarations and illegal exports to prevent penalties and loss of reputation.
- **Policy Changes**
  Pay attention to domestic and international trade policies and export control trends, and adjust export strategies in a timely manner.
- **Cross-border trade compliance requires**
  compliance with the regulatory requirements of the importing country and the completion of necessary certification and inspection procedures.
- **Supply chain coordination**
  strengthens communication with logistics, customs declaration and inspection agencies to ensure smooth export process.

Summary:
The export of tungsten alloy rods involves complex customs supervision and license management. Enterprises must fully understand and strictly abide by relevant laws and regulations and procedures. Scientific export management not only ensures compliance operations , but also helps to enhance the international competitiveness and market expansion capabilities of enterprises. It is recommended that enterprises establish a dedicated trade compliance team , strengthen risk management, and promote the healthy development of export business.

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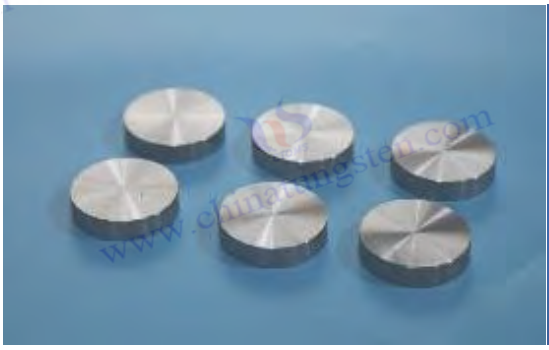
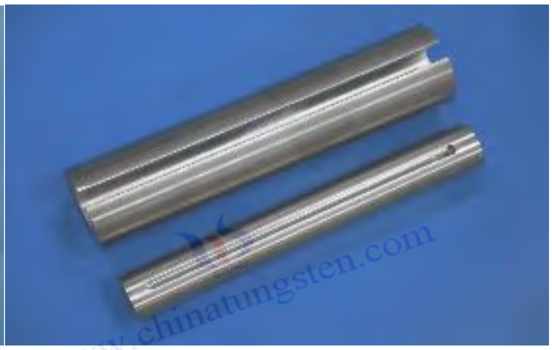

Chapter 9 Market Structure and Development Trend of Tungsten Alloy Rods

9.1 Overview of the Global Tungsten Resources and Alloy Rod Industry Chain

Tungsten, as a rare and important strategic metal, is widely used in high-end fields such as aerospace, military industry, electronics, and medical treatment due to its high melting point, high density, and excellent mechanical properties. As an important product of deep processing of tungsten resources, the market demand for tungsten alloy rods continues to grow, and its industrial chain system is complex and has obvious global characteristics.

9.1.1 Global tungsten resource distribution

- **The main production areas are concentrated in**
  the world's tungsten resources, which are mainly distributed in China, Russia, Canada, Vietnam, Portugal, Austria and other countries.
  - China is the world's largest tungsten ore producer, accounting for more than 80% of global production, with rich tungsten reserves and mature mining technology;
  - Russia and Canada also have large-scale tungsten deposits and have a certain influence in the international market;
  - Vietnam and Portugal are production areas with relatively concentrated tungsten resources and greater potential.
- **Resource Types**
  Tungsten ore mainly exists in the form of chalcanthite ($CaWO_4$), wolframite ($FeWO_4$) and scheelite (WO_3). Ore grade and mining difficulty affect resource development efficiency.

- **Resource and environmental challenges**
  : Tungsten mining faces environmental pressure and resource depletion risks, which prompts the industry to develop in the direction of efficient resource utilization and circular economy.

9.1.2 Current Status of Tungsten Resource Mining and Processing

- **The mining technology**
  adopts a combination of open-pit mining and underground mining, which is flexibly selected according to different ore deposit conditions. Modern machinery and automation technology are gradually promoted to improve mining efficiency and safety.
- **Primary smelting and concentrate production**
  Tungsten ore undergoes beneficiation, roasting and chemical leaching to obtain high-purity tungsten concentrate. The quality of the concentrate directly affects the performance of subsequent tungsten alloy powder and products.
- **Advances in smelting technology**
  Continuous innovations in tungsten smelting technology, including carbon thermal reduction, hydrogen reduction and chemical vapor deposition, have enabled the production of high-purity tungsten.

9.1.3 Tungsten Alloy Rod Industry Chain Structure

The tungsten alloy rod industry chain mainly includes the following links:

1. Tungsten ore, tungsten concentrate and tungsten powder are the basic raw materials for the production of **tungsten** alloy rods.
   The quality and stable supply of raw materials are related to product consistency and cost control.
2. **Powder Metallurgy and Alloy Preparation**
   Through the powder metallurgy process, tungsten powder is evenly mixed with alloy elements (such as nickel, iron, and copper), pressed and sintered. This step determines the organizational structure and performance indicators of tungsten alloy rods.
3. **Forming processing**
   includes machining, heat treatment and surface treatment to ensure that the product meets the design size and performance requirements.
4. **Performance Testing and Quality Control**
   Strict physical, chemical and mechanical performance testing ensures product quality.
5. **Sales and Application**
   Tungsten alloy rods are widely used in aerospace, military, medical, electronics and other fields, and the market demand is constantly expanding.

9.1.4 Characteristics of the globalization of the industrial chain

- **Transnational cooperation in the supply chain**
  The distribution of tungsten ore resources and downstream processing capacity areas do not completely overlap, which has led to the formation of a transnational cooperation pattern in the
  tungsten alloy rod industry chain . China has the advantages of mineral resources and large-scale smelting capabilities, while Europe, the United States, Japan, South Korea and other countries focus on high-end processing and precision manufacturing.
- **Technology and market dual drive**
  Technological progress promotes the performance improvement of tungsten alloy rods, while the diversification of market demand promotes the adjustment of the industrial chain.
- **Trade Flows**
  Tungsten raw materials are mainly exported by resource-rich countries, while processed products are circulated in the international market. As a high value-added product, the trade activity of tungsten alloy rods is gradually increasing.

summary

Although global tungsten resources are relatively concentrated, the tungsten alloy rod industry chain is highly internationalized and complex. Understanding resource distribution and industry chain structure is the basis for grasping the market pattern and development trend of tungsten alloy rods . In the future, with the advancement of technology and the promotion of green manufacturing concepts, the tungsten alloy rod industry chain will be more perfect and promote the high-quality development of the industry.

9.2 Tungsten Alloy Rod Market Size and Growth Trend Analysis

As a high-performance functional material, tungsten alloy rods are widely used in aerospace, military equipment, medical equipment, high-end electronics, nuclear energy engineering, etc. With the transformation and upgrading of the global manufacturing industry and the rise of emerging industries, the market size of tungsten alloy rods has steadily expanded, showing significant characteristics such as demand growth, regional agglomeration, and diversified applications.

9.2.1 Current Global Market Size

- According to data released by the **International** Tungsten Industry Association (ITIA) and market research institutions (such as MarketsandMarkets and Grand View Research), the total market value of global tungsten alloys in 2024 is about **1.3 to 1.5 billion US dollars** , of which tungsten alloy rods account for about 30%, or **400 to 500 million US dollars** . It is expected that by 2030, this figure is expected to exceed **800 million US dollars** .
- **Regional distribution of production and consumption**
  - **China** : The world's largest producer and consumer of tungsten alloy rods, with a complete industrial chain and large-scale manufacturing capabilities, accounting for more than 50% of the market;

- **North America and Europe** : Mainly focusing on high-end applications, focusing on quality and performance, with a high import ratio;
- **Other regions in Asia Pacific** (such as South Korea, Japan, and India): emerging growth markets with strong technology orientation and rapidly growing consumer demand;
- **Middle East and Africa** : Currently limited in scale, but showing potential for growth driven by investments in nuclear energy and medical equipment.

9.2.2 Market Growth Drivers

1. **Rapid development of high-end manufacturing industry**
   - With the rapid development of industries such as aerospace, missile systems, and high-precision instruments, the demand for high-density, high-strength tungsten alloy rods continues to grow;
   - The development of intelligent manufacturing, advanced weapon systems and new energy technologies has further driven the market demand for tungsten alloys.
2. **Expansion of applications in the medical and nuclear fields**
   - Tungsten alloy rods are widely used in radiotherapy equipment, radiation shielding, gamma knife, etc., benefiting from the global aging population and increased medical investment;
   - Nuclear power generation and fusion research have driven the application of tungsten alloy rods in the fields of neutron absorption and high-temperature components.
3. **Supply chain and security strategy promotion**
   - Countries strengthen control over strategic metals, increase the proportion of local manufacturing, and promote the diffusion of tungsten alloy rod production capacity to diversified regions;
   - Although the global exploration of alternative materials continues, there is still no equivalent substitute for tungsten alloy in the short term.
4. **Technological progress increases product added value**
   - The development of technologies such as nano-enhancement, high-purity control, and intelligent manufacturing has continuously improved the performance of tungsten alloy rods and expanded more emerging applications.

9.2.3 Industry growth trend forecast (2025–2030)

years	Global Tungsten Alloy Rod Market Valuation (USD billion)	Compound Annual Growth Rate (CAGR)
2025	5.2	—
2026	5.6	7.7%
2027	6.1	8.0%

2028	6.7	9.0%
2029	7.4	10.0%
2030	8.1	10.3%

Note: The forecast is based on the assumption of continued upward investment in high-end manufacturing and medical nuclear energy. If raw material prices fluctuate or there are breakthroughs in alternative material technology, the growth curve may be adjusted.

9.2.4 Market Development Characteristics

- **for upgrading from low-end to high-end**
  has shifted from tungsten alloy rods for traditional machining to high-end products with high density, high toughness, corrosion resistance and excellent high temperature performance.
- Although China still holds a dominant position as **regional competition intensifies , Europe, the United States and Japan are advancing their local**
  tungsten resource processing capabilities to meet supply chain security challenges.
- **Green and sustainable trends are emerging.**
  Recycling of tungsten resources has become a new growth point, and the technology and policy for recycled tungsten alloy rods are advancing rapidly.

9.2.5 Challenges

- **The price of raw materials fluctuates.**
  The price of tungsten concentrate is greatly affected by resource limitations, environmental protection policies and speculative factors, and cost control has become a difficult point for enterprises.
- **International trade**
  barriers, export restrictions, technical blockades, anti-dumping investigations and other trade issues may affect the cross-border circulation of tungsten alloy rods.
- **Technical barriers in the high-end market:**
  Domestic tungsten alloy rods still face process gaps and certification barriers in some high-tech fields such as aviation and nuclear energy.

summary

tungsten alloy rod market is in a rapid growth stage, benefiting from the development of global high-end manufacturing, medical and energy industries, but also facing challenges such as raw material dependence, technology improvement and trade risks. In the next few years, with the upgrading of manufacturing capabilities and the expansion of application fields, the tungsten alloy rod market will continue to expand. Industry companies should focus on the three major directions of high-end products, global layout and green transformation to seize strategic opportunities.

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9.3 Mainstream manufacturers and competition (China, Europe, America, Japan and South Korea)

The tungsten alloy rod industry has typical dual attributes of technology-intensiveness and resource-dependence. The global market is mainly dominated by countries with rich tungsten resources or leading processing technologies, such as China, Europe, the United States, Japan and South Korea. Enterprises in various regions have formed distinct differences in resource control, technology paths, product positioning and market strategies, which together constitute the current multi-polar competition pattern of the tungsten alloy rod industry .

9.3.1 Chinese Enterprises: Emphasis on Resource Advantages and Large-Scale Manufacturing

As the world's largest tungsten resource country and tungsten processing center, China has a broad enterprise base and a complete industrial chain in the field of tungsten alloy rods . The characteristics of Chinese enterprises are large production capacity, full variety and strong cost control.

- **Representative companies**
  - **CTIA GROUP LTD,** strong control over resources and strong supporting capabilities of the industrial chain.
- **Competitive Advantage**
  - High self-sufficiency rate of raw materials to ensure stable supply;
  - Strong cost control capability and competitive product prices;
  - Quickly respond to customer customization needs and short delivery cycle.
- **Development bottleneck**
  - There is still a gap between China and Europe, the United States and Japan in terms of high-precision processing and extreme performance control;
  - The influence on the international market is relatively limited, and the construction of a high-end certification system is still in progress.

9.3.2 European and American companies: technological barriers and high-end applications dominate

European and American companies have been deeply engaged in high-performance alloy materials for a long time. Relying on their technological advantages in powder metallurgy, high-temperature alloys, nuclear energy materials, etc., they have occupied a dominant position in the high-end application field of tungsten alloy rods.

- **Representative companies**
  - **Plansee Group (Austria)** : A world-leading producer of tungsten and molybdenum alloys, whose products are widely used in aviation, semiconductors and medical devices;

- o **HC Starck Tungsten (Germany/USA)** : Focuses on high-purity tungsten and high-performance tungsten alloys, and masters advanced powder metallurgy and atmosphere control technologies;
- o **Global Tungsten & Powders Corp (GTP, USA)** : It has mature technology in the preparation of high-purity tungsten powder and alloy rods and has a global sales network.

- **Competitive Advantage**
  - o We have profound technical accumulation and own a series of independent patents and core technologies;
  - o Passed high-end certification systems such as AS9100 and NADCAP, and entered the aviation and military supply chains;
  - o The brand effect is strong, and it provides stable services to high-end customers in Europe and the United States.
- **Challenges and Trends**
  - o High cost, long delivery cycle, and weak competitiveness in the mid- and low-end markets;
  - o Faced with pressure from environmental regulations and rising energy costs, some production capacity is being transferred to Eastern Europe or Southeast Asia.

9.3.3 Japanese and Korean companies: driven by precision machining and electronic applications

Japanese and Korean companies have unique advantages in ultra-precision processing and high-purity control of tungsten alloy rods, and their products are widely used in microelectronics, medical treatment and precision instruments.

- **Representative companies**
  - o **Mitsui Mining & Smelting** : Developing a variety of fine-grained reinforced tungsten alloys to serve the electronic packaging and medical industries;
  - o **Tosoh of Japan** : has accumulated technology in the fine processing of tungsten powder and the development of high-density alloys;
  - o **HEMC Co., Ltd. of South Korea** : Focuses on the customized production of high-precision tungsten alloy rods and special-shaped parts, with strong R&D and rapid response capabilities.
- **Technical highlights**
  - o Outstanding ability in preparing high-purity materials ;
  - o Leading in microstructure control and nano-enhancement;
  - o batch and stable processing of complex small-sized tungsten alloy parts.
- **Market Positioning**
  - o Targeting mid-to-high-end markets such as electronics, display devices, and laser components;

- The product unit price is high, the service capability is strong, and it wins with quality and technology.

9.3.4 Summary of global competition landscape and trends

area	Company Features	Technical Level	Market Positioning	Advantages	Disadvantages
China	Resource-led + large-scale manufacturing	Mid-range and high-end coexist	Focus on mid-range, break through to high-end	Low cost and stable supply	Insufficient high-end certification system
Europe and America	Technology driven + brand leading	High-end leadership	Aviation, military, medical	Strong technology and perfect standards	High cost and high price
Japanese and Korean	Precision + Customization	High purity and fine	Electronics and medical applications	High processing accuracy	Small production capacity

summary

global tungsten alloy rod market presents a competitive landscape of "China's production capacity dominates, Europe and the United States occupy the high-end, and Japan and South Korea are deeply involved in precision." In the future, with the development of new material technology, the strengthening of the localization trend of the supply chain, and the intensification of competition in the high-end market, companies in various regions will continue to optimize their strategic positioning. If Chinese companies want to achieve the transformation from big to strong, they need to continue to work hard on material design, precision processing and certification systems; European and American companies need to cope with the pressure of cost and supply chain reconstruction and maintain their technological leadership; Japanese and Korean companies will continue to deepen their market segments and maintain their advantages in high value-added products.

9.4 Raw Material Price Fluctuation and Cost Structure Analysis

tungsten alloy rods is highly dependent on the price of raw materials, especially the price fluctuations of tungsten concentrate, tungsten powder, alloy elements (such as Ni, Fe, Cu), etc., which have a profound impact on the stability and profitability of the entire industry chain. The global tungsten resource reserves are limited, the market is highly concentrated, and driven by supply and demand, policies, environmental protection, geopolitics and other factors, its price shows cyclical fluctuations.

Structure of Tungsten Alloy Rods

tungsten alloy rods is mainly composed of the following parts:

Cost Category	Proportion (reference range)	illustrate
Tungsten Raw Material Cost	50%~65%	Including tungsten concentrate , ammonium paratungstate (APT), tungsten powder, etc., price fluctuations have the greatest impact on the total cost
Alloy element cost	10%~15%	Such as Ni, Fe, Cu, the price fluctuation is smaller than tungsten but still volatile
Energy and auxiliary materials	8%~12%	Electricity, hydrogen, protective gas, mold materials, etc. are affected by energy consumption structure and regional policies.
Labor and management costs	5%~10%	Including salaries, factory rent, administrative expenses, etc.
Equipment and depreciation costs	3%~5%	Large sintering and pressing equipment and their maintenance costs
Environmental protection and safety costs	2%~5%	Especially in China and the EU, investment in environmental protection continues to increase

Note: The cost structure varies depending on the process, origin, production scale and product specifications.

9.4.2 Fluctuation trend of tungsten raw material prices

tungsten is affected by many complex factors. The following are the price fluctuations of the main raw materials of tungsten in recent years:

(1) Tungsten concentrate ($WO_3 \geq 65\%$) price trend

- **2020–2022** : The price will stabilize at around **RMB 95,000 to RMB 110,000 per ton ;**
- **2022-2023** : Affected by the investment boom in new energy, tight supply and environmental protection restrictions , the price rises to **more than 125,000 yuan/ton** ;
- **2024** : Under the influence of domestic policy regulation and global economic slowdown, prices will fall back and fluctuate between **113,000 and 120,000 yuan per ton** .

(2) APT (ammonium paratungstate) and tungsten powder prices

- **RMB 175,000 to RMB 190,000 per ton** in mid-2024 ;
- The price stability of tungsten powder is slightly poor. Due to the great influence of processing technology and particle size specifications, the price often fluctuates between **240,000 and 280,000 yuan per ton** .

(3) Alloy element prices

- Nickel (Ni) prices fluctuate greatly. Affected by the new energy and stainless steel industries, they once exceeded **200,000 yuan/ton in 2023** and stabilized in 2024.

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- The prices of copper (Cu) and iron (Fe) fluctuate relatively little, but are still affected to a certain extent by changes in the international trade situation.

9.4.3 Impact of Raw Material Fluctuations on Business Operations

Impact Dimension	Specific manifestations
Cost control becomes more difficult	tungsten raw materials has squeezed gross profits, especially for small and medium-sized enterprises
Frequent price fluctuations	The purchasing cycle of downstream customers does not match the price fluctuation of raw materials, increasing order uncertainty
Inventory and procurement strategy risks increase	Locking the price of raw materials in advance may lead to price mismatch, affecting cash flow and inventory value
Conductivity differentiation	Leading companies can pass on cost pressures through technology premiums, while small companies have weak bargaining power

9.4.4 Response strategies and trend judgment

(1) Construction of price locking and hedging mechanism

- Companies can use futures or long-term agreements to lock in raw material purchase prices;
- Strengthen cooperation with resource suppliers and establish stable procurement channels.

(2) Product structure optimization and high value-added transformation

- Improve unit gross profit margin by developing tungsten alloy rods with special properties such as high strength and high temperature resistance;
- Hedge against raw material cost fluctuations through process differentiation .

(3) Strengthen energy conservation and cost control in the production process

- Reduce specific energy consumption through energy-saving processes such as isostatic pressing and laser sintering;
- Implement lean production management to improve yield rate and raw material utilization rate.

(4) Green recycling and utilization of recycled tungsten alloy

- Establish a tungsten material recycling system and develop recycled tungsten powder technology;
- The cost of recycled tungsten is significantly lower than that of extracting ore, making it an important way to reduce costs in the future.

summary

Tungsten alloy rod production is extremely sensitive to raw material prices, especially the price fluctuations of tungsten powder and alloy elements, which directly affect the profitability of enterprises. Against the backdrop of global resource strategicization, stricter environmental protection policies and continued growth in high-end applications, high-level fluctuations in raw material costs may become the new normal. In the future, enterprises need to strengthen their risk management capabilities, cope with cost pressures and achieve sustainable development through diversified raw material strategies, high-end products and green manufacturing.

9.5 Interpretation of Industrial Policy and Export Situation

As a rare metal product with high technology content and high added value, tungsten alloy rods are highly affected by industrial policies and international export controls. Especially in the context of global "resource strategy" and "supply chain localization", governments of various countries have introduced corresponding policies to ensure the security of their key material supply chains and strengthen trade supervision of key metals. Enterprises need to accurately grasp the trend of policy changes under the premise of compliance to enhance risk resistance and global competitiveness.

9.5.1 China's tungsten industry policy orientation

(1) Resource protection and total quantity control

- Tungsten is listed as a key mineral protected by the state, and mandatory total production control is implemented;
- Since 2002, the total mining volume control plan has been implemented for tungsten mines, and the mandatory production of tungsten concentrate (WO_3 content 65%) in 2024 is about **110,000 tons** ;
- The country strictly controls illegal mining and cracks down on illegal resource trading.

(2) Industrial upgrading and green transformation

- The "Rare Metal Industry Development Plan" and "New Materials Industry Development Guidelines" encourage the transformation of tungsten resources into high-performance alloys, advanced structural materials, and functional materials;
- of high-end products such as powder metallurgy, high-density alloys, and tungsten-based composite materials , and eliminate high- pollution and inefficient production capacity;
- Enhance the technological breakthroughs and equipment localization capabilities in the field of tungsten alloys, and form a full chain of "resources-products-applications".

(3) Export management and restriction policies

- Tungsten alloy rods and their parent materials are sensitive products on the "Dual-Use Items and Technologies Export Control List" and require an export license in accordance with the law;
- The Ministry of Commerce and the General Administration of Customs jointly supervise and export enterprises must have relevant qualifications and management systems;
- It is prohibited to evade export supervision by concealing declarations or changing product names through a third party. Violators will face fines and freezing of export qualifications.

9.5.2 Changes in the international export environment

(1) Strengthening of “two-way control” between Europe and the United States

- The United States and Europe have included tungsten alloys in the list of "critical minerals" or "strategic materials" and strengthened the review of imported tungsten products;
- Imposing certain trade restrictions on Chinese tungsten products (including tungsten alloy rods), including technical traceability requirements and dual-use review;
- The United States gives priority to purchasing some military tungsten products from domestic suppliers or "friendly countries", forming a technical barrier.

(2) The Japanese and Korean markets are relatively open but have high barriers to entry

- South Korea and Japan have extremely high requirements in terms of technical review and product performance standards, especially in high-precision applications such as medical, electronics and semiconductors, and put forward technical thresholds such as customization and microstructure control for tungsten alloy rods ;
- Enterprises need to pass ISO, JIS, MIL and other series of standard certifications, as well as strict processes such as customer factory audits and batch stability verification.

(3) The market potential of countries along the Belt and Road Initiative is increasing

- The expansion of infrastructure construction and energy investment in countries along the “Belt and Road” such as Central Asia, the Middle East, and Eastern Europe has created new demands for high-density counterweights and radiation protection tungsten alloy products;
- Policies support enterprises in exploring emerging markets through tools such as export credit insurance, cross-border RMB settlement, and tax agreements.

9.5.3 Export situation and risk prevention and control

Main risk types	Explanation and countermeasures
Trade frictions escalate	To deal with potential "anti-dumping investigations" and "source country discrimination" policies in markets such as the United States, product differentiation and avoidance path layout (such as re-export trade) can be adopted.
Certification threshold restrictions	Accelerate the establishment of international standard system certification capabilities, such as AS9100 (aerospace), NADCAP (heat treatment), etc., to enter the high-end supply chain
Export approval delays	The extension of the export license cycle may affect delivery. It is recommended that companies plan the customs clearance cycle in advance and improve their internal compliance preparation capabilities.
Geopolitical volatility	Diversify customer markets to avoid over-reliance on a single country; strengthen collaboration with local partners to diversify risks

9.5.4 Policy recommendations and corporate response strategies

1. **Strengthen policy tracking and information early warning mechanisms.**
   Enterprises should set up full-time teams to pay attention to policy developments released by the National Development and Reform Commission , the Ministry of Commerce, the

Customs, and international industry associations, and proactively adapt to regulatory changes.

2. **Build a compliant export system and qualification management capabilities**
    - Apply for necessary qualifications such as "dual-use item license" and "export registration certificate";
    - Establish a product traceability system and a full-process customs declaration document archiving mechanism.
3. **Actively participate in the construction of international standards**
    and jointly with scientific research institutions participate in the formulation of new ISO/ASTM standards to enhance international voice and improve product quality system construction.
4. **Expanding diversified international markets**
    - Deeply cultivate high-end customers in Europe, America and Japan;
    - At the same time, we will develop emerging markets such as the Middle East, India and Southeast Asia to reduce the risk of geopolitical concentration.

summary

As a strategic material, the export situation of tungsten alloy rods is deeply affected by policy guidance and international environmental fluctuations. China implements resource control and high value-added transformation strategy, Europe and the United States strengthen technology and trade barriers, and Japan and South Korea guide product entry with technology certification. Enterprises should accurately understand and adapt to these policy logics, and establish their own international competitive moat by improving technical content, improving compliance systems and expanding diversified markets.

9.6 Forecast of future demand for tungsten alloy rods in high-end manufacturing

As the global manufacturing industry accelerates towards a new era of high performance, lightweight, intelligent and green, higher standards and diversified demands are put forward for materials. Tungsten alloy rods have become an indispensable key material in high-end manufacturing fields such as aerospace, nuclear energy, military industry, and electronic medical due to their excellent high density, high melting point, strong mechanical properties, radiation resistance and thermal stability. In the future, the upgrading of these industries will continue to promote the demand for tungsten alloy rods, performance requirements and application depth.

9.6.1 Overview of Development Trends of High-end Manufacturing

Industry Direction	Development Trend	Requirements for tungsten alloy rods
Aerospace	Develop towards higher thrust-to-weight ratio and stronger load resistance	High specific gravity + high toughness + controllable inertia structural parts

Hypersonic weapons	High-speed flight + high-temperature shock environment	Thermal shock resistance + Thermal stability + Cavitation fatigue resistance
Nuclear fusion/fission	Extreme temperatures + high radiation intensity	Radiation resistance + high temperature strength + neutron absorption
Medical equipment	Miniaturization and precision	High density + processability + material biocompatibility
Semiconductor and Electronic Packaging	High power density + thermal management challenges	Thermal conductivity + Packaging strength + Small precision structure
Precision Machinery and Robotics	High dynamic control + inertia customized components	High density + geometric precision control capability

9.6.2 Forecast of future demand in key areas

(1) Aerospace and inertial control components

- With the accelerated development **of satellite constellations** , **reusable rockets** , and **commercial aircraft** , the demand for tungsten alloy rods for counterweights and inertial control parts has increased significantly;
- The new generation of aircraft places higher demands on the dimensional accuracy, mechanical strength and reliability of materials;
- It is estimated that by 2030, the average annual growth rate of demand for tungsten alloy rods in the aerospace field will be **10~12%** .

(2) Nuclear energy and fusion energy engineering

- tungsten materials in nuclear fusion projects such as ITER and CFETR continues to deepen, and the application of tungsten alloy rods in radiation shielding and control rod structures continues to expand;
- The fourth generation of fission reactors (fast neutron reactors, molten salt reactors) also list tungsten alloys as candidates for structural materials;
- China, the European Union, the United States, Japan, and other countries have all initiated projects to develop tungsten-based nuclear materials;
- By 2035, the compound annual growth rate of tungsten alloy rods in the nuclear energy field is expected to remain **above 13%** .

(3) High-end medical equipment

- Medical tungsten alloy rods are used in **radiotherapy accelerators** , **gamma-ray knives** , **radiation source protection structures** , etc.
- The aging population and the rapid growth in demand for cancer treatment equipment;
- Especially in the field of **high-density and low-impurity medical tungsten rods** , Chinese companies are accelerating the breakthrough of European and American standard barriers;
- It is predicted that the global medical tungsten alloy rod market will reach **more than US$300 million by 2030** .

(4) Intelligent manufacturing and high-end machine tools

- High-speed, high-inertia tool counterweights, automated tooling fixtures, etc. are gradually using high-density tungsten alloys to replace traditional steel;
- tungsten alloy rods for CNC machine tools and high-precision spindle components have become a new growth point;
- Demand in Asia (China, Japan, and South Korea) is particularly significant, with an estimated growth rate of **8-10% in the next five years** .

(5) National Defense and Hypersonic Weapon Systems

- As tactical weapons evolve towards high-speed penetration, track adjustment, and miniaturization, tungsten alloy rods are increasingly used in bullet cores, balanced tail compartments , etc.
- for **armor-piercing projectiles and kinetic weapons** will focus on upgrading to nano-strengthened, high-density, and high-toughness materials;
- Military-grade tungsten alloy rods are expected to maintain an average annual growth rate of **8-9%** .

9.6.3 Performance Technology Trends

Performance Indicators	Development direction	Example of technology path
Specific gravity control accuracy	Within ±0.01 g/cm³	Target pressing + CNC extrusion forming
Thermal shock resistance	Thermal gradient shock exceeding 1000℃	Addition of ZrC / La_2O_3 composite ceramic particles
Microstructure uniformity	Grain size is controlled to within 5μm	Nano powder + vacuum sintering
Processing accuracy	φ±0.005mm, surface Ra＜0.1μm	Fine grain densification + superfine grinding
Radiation resistance	Neutron absorption/gamma radiation protection enhancement	B/C and other elements coating/co-sintering

9.6.4 Enterprise development suggestions and forward-looking layout

1. **The product structure develops towards high-performance customization and** develops series of products for different applications, such as: aerospace inertial counterweight series, medical radiotherapy shielding series, semiconductor heat dissipation series, etc., to enhance customer stickiness.
2. **Establish a high-end customer certification system,** plan AS9100, ISO13485, MIL and other quality systems in advance, and expand the global high-end manufacturing customer base.

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3. **Investing in green and recycling manufacturing systems**
   takes tungsten alloy powder recycling, green sintering and low-carbon technology as the fulcrum to create new advantages in the future supply chain .
4. **Embracing smart manufacturing and digital monitoring,**
   we introduce the concept of Industry 4.0, realize digital monitoring and data-driven throughout the entire material preparation process, and improve consistency and yield.

summary

Tungsten alloy rods will usher in a new round of development opportunities in the next decade, which will be high-end, segmented and globalized. Aerospace, nuclear fusion, medical protection, precision manufacturing and defense industries will continue to be the core driving force for their demand. Only by continuously exerting efforts in material innovation , quality system, market expansion and technology upgrading can enterprises win the initiative in development in this round of high-end manufacturing wave.

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Chapter 10 Research Hotspots and Frontier Technologies of Tungsten Alloy Rods

10.1 Study on the Densification Process of High-Density Tungsten Alloy Rods

tungsten alloy rods has a decisive influence on their mechanical properties, thermal conductivity, corrosion resistance and service life. Achieving tungsten alloy rods **close to theoretical density (>98.5%) or even close to full density** is an important research hotspot in the current field of materials engineering and powder metallurgy. The quality of the densification process directly determines the structural integrity, microstructure uniformity and reliability of the product in high-end applications (such as nuclear fusion structural parts, missile balance parts, and high-power electronic heat sinks).

10.1.1 Basic principles and index requirements of densification

Densification refers to the process in which the pores between particles are gradually closed, the particle interfaces are bonded, and the grains are effectively stacked and diffused by applying temperature, pressure or other energy input to the powder compact.

Key Metrics:

- **Bulk density ≥ 18.5 g/cm³ (W content> 90% alloy)**
- **Porosity ≤ 1.5%**
- **No obvious inclusions, cracks or pore concentration areas**
- **Grain size can be controlled below 20μm**

10.1.2 Traditional sintering densification technology

(1) Conventional vacuum sintering

- Typical process temperature: **1450–1550°C**
- Applicable to W-Ni-Fe, W-Ni-Cu systems
- Advantages: mature technology, suitable for batch production
- Disadvantages: Pores are difficult to completely drain, and liquid phase is required to promote densification

(2) Liquid phase assisted sintering

- The formation of a critical liquid phase by Ni or Cu promotes the rearrangement of particles at the sintering temperature
- Can improve tissue uniformity and bonding ability
- There are risks of "liquid phase segregation" and "grain growth", and the liquid phase ratio needs to be strictly controlled

(3) Multi-stage sintering and delayed sintering

- Multi-step heating or keeping different temperature zones for a certain time helps to exhaust and control grain size
- Especially effective for ultrafine powders or nano powders

10.1.3 Advanced Densification Technology Path

(1) Hot Isostatic Pressing (HIP)

- Apply isotropic gas pressure (100–200 MPa) at high temperature to cause the internal micropores to collapse
- Can increase density to >99.5%
- Disadvantages: Expensive equipment, long cycle, suitable for post-processing of high-end parts

(2) Spark plasma sintering (SPS)

- Rapid densification by high current pulse + axial pressure
- Fast heating rate (up to 100°C/min) and short sintering time (within a few minutes)
- Can maintain nano-grains and inhibit excessive growth
- Disadvantages: Product size is limited by the mold, suitable for small high-value materials

(3) Microwave sintering

- Using tungsten's absorption of microwaves to achieve uniform internal heating
- High thermal efficiency and fast densification rate, but arc and hot spot issues need to be resolved

(4) Laser-assisted densification

- tungsten alloy rods with special-shaped structures or multi-layer composite structures.
- The technology is still in the research and experimental stage, and industrialization needs further breakthroughs

10.1.4 Effect of Material Factors on Densification

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- **Powder particle size** : The smaller the particle size (especially <1μm), the lower the densification temperature and the faster the speed, but abnormal sintering neck growth is more likely to occur;
- **Powder morphology** : Spherical powder is easier to be dense, while flaky or angular powder is more likely to form void aggregation during sintering;
- **Impurities and oxygen content** : Impurities such as Si, O, and C tend to form interlayers or second phases at the interface, hindering the densification process;
- **Distribution of alloy elements** : Uniform distribution of Ni/Cu can optimize the liquid phase diffusion path and improve density.

10.1.5 Microscopic Mechanisms of Densification

- **Diffusion mechanism** : Bulk diffusion and grain boundary diffusion are dominant, and adding active elements (such as La and Zr) can promote short-range diffusion;
- **Particle rearrangement theory** : In the presence of liquid phase, particles tend to the minimum energy configuration, forming a dense stacking structure;
- **Pore migration and contraction** : small pores gather toward large pores, or close under the action of thermal-mechanical coupling to form a complete dense body;
- **Grain growth inhibition** : Control the heating rate and add grain boundary inhibitors (such as rare earth oxides) to maintain a fine-grained structure.

10.1.6 Application Examples and Research Progress

- **Institute of Metal Research, Chinese Academy of Sciences** : Using SPS to achieve a W-5Ni-2Fe alloy density of 99.4% and an average grain size of 6.2μm;
- **Plansee , Austria** : Commercial HIP+isothermal forging technology is applied to high-density tungsten rods for aerospace use, with a porosity of less than 0.3%;
- **China Tungsten High-Tech** : Developed liquid phase and microwave composite densification process to make the density of W-Ni-Cu rod reach above 18.9 g/cm³, which is widely used in military projectile cores.

10.1.7 Future Development Trends and Challenges

Development direction	Technical Path	challenge
Nanoscale powder densification	Ultra-fast sintering and cold sintering	Powder agglomeration and oxidation inhibition are difficult
Densification of Large Size Tungsten Alloy Rods	Multi-stage HIP + hot forging combination	Thermal stress control, cost control
Design of dense composite structure	Core-shell powder, gradient structure materials	Process precision and equipment capacity limitations

Intelligent sintering process monitoring	Online density assessment + feedback control	It is difficult to integrate perception technology and AI algorithms

summary

high-density tungsten alloy rods is a complex system engineering in materials science that integrates powder engineering, thermodynamic control, interface physics and processing technology. In the future, with **the continuous improvement of high-end application demand, the continuous iteration of densification technology, and the in-depth integration of intelligent manufacturing concepts** , the densification process of tungsten alloy rods will further develop in the direction of precision, greenness and personalization.

10.2 Intelligent Manufacturing and Automated Tungsten Alloy Rod Production Line

As the global manufacturing industry transforms towards "high-end, intelligent, and green", the tungsten alloy rod production field is also gradually moving from the traditional mass production model to the **intelligent manufacturing** stage. By introducing new generation manufacturing technologies such as cyber-physical systems (CPS), industrial Internet of Things (IIoT), artificial intelligence (AI), and digital twins, creating intelligent factories **with high automation, strong quality consistency, and high response flexibility** has become the core strategic direction of advanced tungsten material companies.

10.2.1 Necessity of Intelligent Manufacturing of Tungsten Alloy Rods

Drivers	illustrate
Diversified product specifications	demand for customized products with different sizes, alloy compositions and organizational structures is increasing
Cost and efficiency pressure	Rising labor costs, energy consumption control, and quality fluctuations bring production challenges
Quality stability requirements	Aviation, nuclear energy, medical and other fields have extremely high requirements for batch consistency
Compliance and traceability pressure	International certification systems require full process traceability and complete production data records
Safety and environmental protection requirements	Powder processes are flammable and explosive, automation helps improve safety levels

10.2.2 Key Modules of Smart Manufacturing Production Line

Intelligent tungsten alloy rod production lines usually cover the complete process chain from **powder preparation → forming → sintering → heat treatment → processing → testing and**

packaging , integrating automation equipment and information systems to achieve end-to-end collaborative control.

(1) Automatic powder mixing and blending system

- Accurately control the proportion of various tungsten-based powders and added elements;
- Equipped with automatic weighing scale, vacuum feeding system, closed ball mill and drying system;
- Cooperate with MES system to realize formula and batch data management.

(2) Intelligent pressing unit (molding/isostatic pressing)

- Molding: Automatic press with servo hydraulic system and position closed loop control;
- Isostatic pressing: Intelligent autoclave control system with remote presetting and process curve management;
- Realize the integration of automatic loading-pressing-demolding.

(3) Sintering and atmosphere control automatic line

- Automatic temperature and gas controlled vacuum furnace or hydrogen furnace;
- Equipped with track-type material rack conveying system to achieve continuous sintering;
- Remote scheduling of process parameters and real-time atmosphere quality monitoring (online analysis of O_2 and H_2 content).

(4) Integrated control of heat treatment and densification

- Equipped with hot isostatic pressing (HIP) automatic loading and unloading system;
- Cooperate with high temperature forging or extrusion process to form high density and uniform organization processing capability;
- The temperature and pressure curves are automatically controlled, and process data records are uploaded to the cloud.

(5) CNC machining and online testing system

- CNC lathes, grinders, and polishing lines are connected to the MES system;
- CCD vision and laser diameter measuring instrument monitor the size deviation in real time;
- The machining parameters are automatically adjusted to support adaptive machining.

(6) Automatic packaging and labeling

- Intelligent packaging line realizes vacuum, desiccant filling, and anti-vibration buffer configuration;
- Barcode/ QR code + RFID automatic label printing and traceability system.

10.2.3 Digitalization and Information System Support

System Type	Function
MES (Manufacturing Execution System)	Realize production planning management, equipment scheduling, batch traceability, and process execution monitoring
SCADA System	Real-time collection of key parameters such as temperature, atmosphere, pressure, current, etc. and visual display
QMS (Quality Management System)	Establish a full-process quality control process to achieve defect warning and statistical process control (SPC)

ERP system linkage	Integrate orders, procurement, inventory and manufacturing to form a closed-loop management
AI-assisted decision-making engine	Analyze multiple batches of data, optimize parameter settings, and improve the first-time pass rate
Digital Twin System	Build a virtual production model to achieve process optimization, equipment predictive maintenance and simulation

10.2.4 Current bottlenecks and future directions

Key Challenges	Performance	Development direction
High cost threshold	The initial investment in automation equipment is large	Large-scale manufacturing + government support + phased investment
Poor adaptability to special-shaped workpieces	Most of the existing equipment is standard bar specifications	Develop modular intelligent units to adapt to multi-shape processing
Data system silos	Inconsistent interfaces between information systems	Promote open standards and industrial protocol unification (such as OPC UA)
Insufficient human-machine collaboration	Human intervention is still required in key links	Strengthening human- machine collaboration and virtual-reality integrated manufacturing

10.2.5 Future Technology Trend Outlook

1. **Edge computing and AI edge deployment** : Deploy AI smart terminals in key process links to achieve real-time edge monitoring, parameter self-adjustment and equipment status prediction.
2. **Multi- source data fusion analysis** : Fusion of multiple sensor data such as images, acoustics, thermal imaging, vibration, etc. to achieve comprehensive judgment of product quality and defect location.
3. **Low-carbon manufacturing and carbon footprint tracking system** : Evaluate the carbon emissions of tungsten alloy rods throughout their life cycle and establish a green manufacturing evaluation system.
4. **Cloud manufacturing and flexible collaborative network** : Through 5G+Industrial Internet, upstream and downstream manufacturing resources are connected to achieve multi-factory collaborative production scheduling and remote process configuration.

summary

tungsten alloy rods is at a critical stage of transition from "partial automation" to "full process intelligence". In the future, with the deep digitization of core process parameters, the enhancement of equipment intelligence capabilities and the interconnection and integration of management systems, tungsten alloy rod manufacturing will gradually achieve a fundamental transformation from "experience-driven" to "data-driven", and promote the entire high-performance metal materials industry into a new era of intelligence.

Integrated Development of Tungsten Alloy Rods and Additive Manufacturing

With the accelerated application of additive manufacturing technology in aerospace, nuclear energy, military and medical fields, traditional high-performance alloy materials are facing new challenges of complex shapes, customized organization and efficient manufacturing. Tungsten alloy, as a structural and functional material under extreme conditions, is gradually entering **the material system of precision components that can be additively manufactured** . Tungsten alloy rods are not only used as a source of printing parent materials (wires, powders), but are also gradually integrated with additive manufacturing , entering a variety of application scenarios such as **direct printing of functional parts and mixed manufacturing of molds and metallurgies .**

Technical Value of Tungsten Alloy Materials Adapted to Additive Manufacturing

characteristic	Additive Manufacturing Demand	Corresponding tungsten alloy advantages
Very high melting point	>3000°C hot melt process	Tungsten-based alloys are heat-resistant and corrosion-resistant, making them suitable for printing parts in extreme thermal fields.
High Density	Functional counterweight, radiation protection structure	AM can print complex counterweights/hollow structures to achieve lightweight
Radiation Shielding	Nuclear fusion/medical equipment applications	Customizable neutron absorption structural parts to improve integration
Thermal conductivity	Heat sink, nozzle, microchannel cooling	AM allows the manufacture of highly complex cooling channels
Controllable organization	Microstructure Optimization	AM achieves directional solidification/gradient composition control

10.3.2 Types of additive manufacturing processes applicable to tungsten alloys

(1) Laser Powder Bed Fusion (LPBF)

- Principle: The laser melts the metal powder layer by layer and rapidly cools and solidifies;
- Advantages: High printing accuracy, capable of achieving complex microstructures;
- Suitable powder: spherical W, W-Ni-Fe, W-Cu alloy powder;
- Challenge: High melting point leads to low laser absorption efficiency and high crack tendency.

(2) Electron beam melting (EBM)

- Principle: Use electron beam with high energy density to melt tungsten powder;
- Suitable for high melting point metals, such as pure tungsten or W-Ta alloy;
- It has the advantages of vacuum environment and low oxygen content;
- Used in high temperature components such as aerospace propulsion system nozzles.

(3) Directed Energy Deposition (DED)

- Principle: Synchronous powder feeding or wire feeding + laser/electron beam/plasma source;
- Large-sized tungsten alloy structures that can achieve near-net shape ;
- Suitable for reconstruction , repair and thickening of tungsten alloy rod segments and high temperature parts.

(4) Fused Filament Fabrication (FDM Metal Edition) + Debinding Sintering

- Use metal powder + polymer binder for extrusion molding;
- After printing, degreasing and sintering are performed to achieve a dense structure;
- Tungsten alloys have the potential to produce small, low-cost customized parts;
- It has been commercialized for use in W-Cu microwave devices, counterweights, etc.

10.3.3 Key Technical Difficulties of Tungsten Alloy AM

question	Performance	Coping strategies
High melting point materials are difficult to melt	Insufficient laser energy or difficult molten pool control	Increase laser power, use preheated substrate
Powder oxidation sensitive	Oxidation inclusions or pores are easily formed during printing	Use high purity argon protection / vacuum printing system
Thermal cracks and residual stress	Rapid cooling causes crack formation	Use preheated platform and optimized scanning path
Poor material flowability	Uneven powder accumulation and unstable molten pool	Powder spheroidization modification, use of equal-size mixed powder
component segregation	The melting point of W is very different from that of alloy elements	Homogenous premixing using mechanical alloying

10.3.4 Application Examples and Research Progress

- **NASA & ORNL** :
  Used DED technology to print pure tungsten nozzle modules, which were successfully used in high-temperature thrust tests; developed W-Re alloy structural parts for nuclear thermal propulsion tests.
- **Institute of Metal Research, Chinese Academy of Sciences** :
  Through LPBF printing of W-5Ni alloy, the density reached more than 97% after optimizing the laser parameters, the microstructure was uniform, and the crack suppression was good.
- **Fraunhofer Institute, Germany** :
  Established W-Cu powder LPBF printing process for high heat flux electronic packaging and successfully realized embedded microchannel heat sink structure.

- **Tomsk University of Technology, Russia** :
  Exploring the 3D printing path of W-Mo-Ta alloy for research on the inner wall materials of high-temperature plasma containers.

Coupling Development Model of Tungsten Alloy Rods and Additive Manufacturing

model	describe	Application Value
Additive + subtractive composite manufacturing	Tungsten alloy rods are prefabricated into rough blanks and then AM is used to achieve microstructure enhancement or functional cladding	Reduce costs and improve performance
Additive tooling manufacturing	Complex molds made with AM for reverse powder pressing of rods	Suitable for batch production of special-shaped bars
Rod → Wire → Wire feeding printing	High purity tungsten alloy rods are drawn and used for DED printing of large size components	Establish a complete material-process chain
Rod performance modification	Printing local functional layers (anti-oxidation layer, slow-release agent, etc.) on the surface of tungsten rods	Improve service function and lifespan
Evolution of digital twin structural parts	Using AM to realize gradient density structural parts, such as inertia adjustment rods and energy absorption rods	Achieve directional performance control design

10.3.6 Future Development Trends and Path Suggestions

1. **Build a special tungsten alloy AM powder system**
   to develop tungsten alloy powder with optimized particle size distribution, high sphericity, low oxygen content and strong fluidity, and promote standardization.
2. **Equipment and energy source upgrades**
   include development of higher energy density laser/electron beam equipment and intelligent control platforms to adapt to tungsten-based material printing.
3. **Multi-scale tissue control and simulation**
   introduces thermal-stress coupling simulation and process parameter inversion algorithm to achieve precise control of composition-structure-performance mapping.
4. **The mass production and verification of high-end components**
   have shifted from single-piece trial production to large-scale consistency, and a forming-heat treatment-testing standard system has been established to adapt to aerospace, nuclear energy, medical equipment and other fields.
5. **the tungsten alloy-AM integrated production line**
   constructs an integrated "printing factory" from tungsten alloy rod raw material preparation - spheroidized powder production - printing forming - post-processing - testing, improving the control of the entire process.

summary

tungsten alloy and additive manufacturing provides unprecedented possibilities for solving traditional processing problems and realizing complex component manufacturing. With the continuous improvement of material adaptation, equipment capabilities and process standards, tungsten alloy rods will no longer be just terminal products, but will also become the source material , core component and composite technology carrier of 3D printing, helping the metal manufacturing industry enter a new era of intelligence, functionality and precision.

10.4 Comparison and technical paths of high performance alloy alternative materials

With the development of new material technology, tungsten alloys are facing competition and substitution from a variety of new high-performance alloys in some application scenarios. Especially in the fields of aerospace, nuclear energy, electronic heat dissipation and high-temperature structures, customers' multi-dimensional requirements for material performance are constantly increasing, forcing tungsten alloys to continue to evolve in the direction of lighter, stronger, more resistant to high temperatures and more environmentally friendly.

At the same time, a variety of alternative materials with "similar functions" or "obvious cost-effectiveness advantages" are accelerating industrialization, which has a profound impact on the market structure of tungsten alloys.

10.4.1 Main performance advantages and limitations of tungsten alloy

Performance Dimension	Advantages	Limitations
density	Extremely high (19.3 g/cm³), irreplaceable in counterweight, protection, and inertial systems	High density brings processing difficulties and transportation costs
Melting point and thermal stability	Melting point up to 3422°C, suitable for extreme high temperature environments	High temperature processing and welding are difficult, and thermal stress is large
Radiation resistance	Excellent neutron absorption and gamma ray shielding performance	Protective layer support is still needed in highly corrosive nuclear environments
Thermal conductivity	Second only to copper and silver, suitable for heat sink/heat dissipation structure	It is difficult to balance thermal conductivity and oxidation resistance
Machinability	After alloying (such as W-Ni-Fe), it has certain processability	Pure tungsten or high tungsten ratio alloys are still difficult to process
Price and resource guarantee	China has abundant resource reserves and stable supply	High purity tungsten is expensive and difficult to process

10.4.2 Comparative Analysis of Typical High-Performance Alternative Materials

Material	Melting point/density	Typical advantages	limitation	Application Overlap

Molybdenum Alloy (Mo)	~2620°C / 10.3 g/cm³	Lightweight, good thermal conductivity, excellent formability	Weak corrosion resistance, lower temperature resistance than tungsten	High temperature electrodes, thermal conductive sheets, electronic heat dissipation structures
Tantalum Alloy (Ta)	~3017°C / 16.6 g/cm³	Corrosion resistance, good ductility	Expensive and scarce resources	Nuclear reactor materials, biocompatible materials
High Entropy Alloy (HEA)	Variable melting point / medium density	Multi-level control, corrosion resistance/high strength	Complex process, R&D stage	Aviation hot end components and structural parts
Ceramic Matrix Composites (CMC)	>2000°C / low density	High temperature strength and lightweight	Brittle, poor impact resistance	Aerospace nozzles, thermal insulation structures
Tungsten copper composite material (W-Cu)	High/Medium Density	Strong thermal conductivity, arc resistance, thermal shock resistance	High cost, average strength	Spot welding electrodes, heat sink modules
Carbon-based materials (C/C, graphite)	High/ Very Light	Extremely light, thermal shock resistant, and ablation resistant	Easy to oxidize, not corrosion resistant	Nozzle, missile insulation

10.4.3 Differentiation strategy of tungsten alloy under substitution trend

1. **Functional segmentation application strategy** :
   - It is still irreplaceable in situations requiring extremely high density and inertial performance (inertial navigation systems, dynamic balancing weights);
   - In nuclear energy and high-energy physics experiments, its neutron absorption ability is superior to other metals and has the advantage of long-term stability.
2. **Improve performance boundary strategy** :
   - Improve its high temperature strength and impact toughness through rare earth element strengthening and nano powder densification technology;
   - Develop composite structures (such as tungsten/ tantalum bimetal , tungsten-clad copper composites, etc.) to expand multifunctional application areas.
3. **Manufacturing Collaboration Strategy** :
   - with additive manufacturing , ultra-precision machining, and high-energy beam welding technology to improve the feasibility of complex structures;

- o Combine dissimilar materials (such as titanium alloys and nickel-based alloys) for multi-material collaborative manufacturing and functional integration.

4. **Green environmental protection and full life cycle strategy** :
   - o Establish a closed-loop system of recycling, reprocessing and reuse to meet environmental regulations and resource sustainability requirements;
   - o Promote RoHS/REACH compliant low -pollution formulas and processing technologies.

10.4.4 Comprehensive comparison: the status of tungsten alloy in the future material system

Dimensions	Tungsten Alloy	Advantages and disadvantages of alternative materials	Development Strategy
High-density protection	Obvious advantages	Only tantalum and tungsten copper can partially replace it, but the cost is higher	Maintaining a dominant position
High temperature structural parts	powerful	HEA, CMC, etc. are competitive	Strengthen alloy system and develop composite materials
Heat sink and heat dissipation	Available	W-Cu and Mo are more advantageous	Multi-material composite path
Nuclear energy structure	excellent	Tantalum and Mo have some applications	Surface coating + multi-layer alloy
Cost and environmental protection	Disadvantages	Mo, C/C are lighter and cheaper	Establishing a green manufacturing system

10.4.5 Technical Path Recommendations and R&D Directions

1. **Multi-component alloy optimization** :
   - o Develop ternary/quaternary systems such as W-Mo-Re and W-Ta-Ni, taking into account high-temperature strength, ductility and processability.
2. **Composite material development** :
   - o Design tungsten/ceramic, tungsten/metal, and tungsten/graphite composite structures to maximize interface strengthening and multifunctional performance.
3. **Construction of advanced process platform** :
   - o Invest in LPBF, DED, HIP+forging, vacuum diffusion welding and other platforms to explore the collaborative forming of tungsten alloy + alternative materials.
4. **Service simulation and reliability database establishment** :
   - o Build a high temperature-irradiation-corrosion multi-field coupling simulation platform to evaluate the service life and economy of new materials.
5. **"Tungsten+" development strategy** :

- o Launched multifunctional integrated structural units with tungsten as the core, such as "tungsten-inertia module" and "tungsten-heat dissipation-protection integrated block".

summary

Although a variety of high-performance materials are posing potential replacement pressure on tungsten alloys, due to its core advantages in density, radiation shielding and extreme environmental adaptability, tungsten alloys will continue to maintain an irreplaceable position in many key areas for a long time. In the future, we should focus on both material upgrading and manufacturing integration, build a **"irreplaceable + synergistic integration"** development pattern for tungsten alloys, and further consolidate its strategic position in high-end manufacturing.

10.5 Performance evolution of tungsten alloys under extreme service conditions in the future

Tungsten alloys have long been used in core components in extreme environments due to their extremely high melting point, high density, good thermal conductivity and neutron absorption capacity, such as the first wall of nuclear fusion devices, aerospace nozzles, reactor neutron shields, and hypersonic aircraft thermal protection structures. However, under these working conditions, the material will face **strong heat loads, severe thermal stresses, radiation damage, gas erosion, and multi-field coupling degradation effects** . A deep understanding of the performance evolution during its service is the key to ensuring the long-term and stable service of tungsten alloy structural parts.

10.5.1 Classification and characteristics of extreme service environments

Environment Type	Characteristic parameters	Typical application scenarios
High temperature thermal shock	>2000°C, heat flux>10 MW/m^2	Aerospace nozzles, plasma heaters, and the first wall of nuclear fusion
Strong irradiation field	Neutron flux > 10^{25} n/m^2 with gamma radiation	Nuclear fission/fusion reactor
High Impact /High Strain Rate	Shock waves, blast loads, inertial acceleration	Ballistic armor-piercing body, kinetic weapon counterweight
Chemical corrosion and oxidation	High temperature oxidizing atmosphere, liquid metal coolant	Aircraft reentry stage, large cooling system
Vacuum-thermal cycle environment	Frequent alternation of vacuum + thermal stress	Spacecraft shell structure, deep space exploration probe

10.5.2 Microstructure and Performance Evolution Mechanism

(1) High temperature recrystallization and grain coarsening

- Long-term service at high temperature can easily lead to grain boundary migration and grain growth;
- This leads to decreased strength and poor plasticity, especially for fine-grained tungsten alloys;
- can be delayed by doping (La_2O_3 , Y_2O_3) or grain boundary pinning strategy.

(2) Irradiation-induced dislocation accumulation and bubble formation

- Fast neutron irradiation produces dislocation loops and vacancy-interstitial pairs;
- He/H gas injection leads to nanocavitation and even “bubble chains”;
- It will cause material embrittlement, decreased thermal conductivity, and dimensional changes (expansion);
- Solutions include: nanocrystallization, interface design, and He deposition barrier structure.

(3) Thermal fatigue and thermal shock corrosion

- Cyclic heating-cooling can cause crack initiation and propagation;
- At high heat flux density (>20 MW/m^2), the surface of the material is prone to "cracking" or erosion;
- Surface pretreatment (roughening) and functional coating (W-Re, W- TaC) can improve impact resistance.

(4) Oxidation and corrosion degradation

- high temperatures , tungsten easily reacts with O_2, H_2O, etc. to generate WO_3 , which increases evaporation losses ;
- Liquid metal coolants such as PbLi have strong permeability to grain boundaries;
- Dense surface coating and oxidation-inhibited alloying are the mainstream coping strategies.

10.5.3 Performance Degradation Behavior and Life Prediction Model

Evolutionary behavior	Performance impact	Modeling approach
Recrystallization and grain growth	Reduce strength and toughness	Grain growth kinetics model
Thermal fatigue crack growth	Structural failure	Paris formula, Coffin-Manson model
Radiation embrittlement	Decreased elongation and fracture toughness	Rate theory + MD simulation
Oxidative evaporation	Mass loss and thermal conductivity degradation	Arrhenius reaction rate + multi-field coupling model
He cavitation expansion	Dimensional changes, structural distortion	Cluster dynamics model

10.5.4 Adaptability Optimization in Typical Application Scenarios

◉ Fusion reactor tungsten alloy first wall (such as ITER plan)

- Requires neutron flux resistance >10^{26} n/ m² and high heat flux stability;
- Develop ultrafine grain W, W-Re alloys, and W/ steel functionally graded structures;
- Research direction: He bubble control, microcrack self-repair mechanism.

◉Hypersonic vehicle leading edge materials

- Stamping heating causes local temperatures to reach 2500°C+, resulting in severe thermal shock ;
- W-based ceramic composites or tungsten fiber reinforced structures can be used;
- The coating system needs to be resistant to oxidation, have high radiation transmittance and low radiation transmittance.

◉Armor -piercing core/kinetic energy projectile

- The impact acceleration reaches 10^4 ~10^5 g, causing severe shearing and deformation;
- Doped W-Ni-Fe alloys are designed to improve fracture mode control;
- The dynamic strength and fracture toughness under high strain rate need to be examined in detail.

◉Medical radiotherapy scatterers/shielders

- Requires precise dose control and stable geometry;
- The dimensions and physical properties need to remain stable in an irradiated/temperature-rising environment;
- Surface treatment and laser repair can extend service life.

10.5.5 New Strategies for Material Optimization and Structural Design

1. **Gradient organization and multi-scale structure design**
   - o Functionally gradient materials (FGM) that achieve corrosion resistance in the surface layer, high strength in the middle layer, and toughness in the core layer.
   - o Additive manufacturing + diffusion welding is used to achieve "customized structure".
2. **Interface strengthening and heterogeneous grain boundary control**
   - o High-energy grain boundaries are introduced through hot isostatic pressing + rapid cooling process to enhance radiation resistance;
   - o The multiphase interface acts as a He cavitation "trap", slowing down expansion and embrittlement.
3. **Radiation-resistant coatings and self-healing systems**
   - o Use thin layers of high melting point ceramics such as ZrC and HfN to prevent surface oxidation/penetration;
   - o Develop small-scale structures that can self-repair in irradiation fields , such as doping Bi and Cr.
4. **AI-driven service degradation prediction**
   - o Combining high- throughput experiments + machine learning to predict performance degradation under complex working conditions;
   - o Build a tungsten alloy "lifetime database" and digital material design platform.

summary

tungsten alloys in extreme environments in the future is a multidisciplinary, multi-scale cross-cutting frontier research topic. Although its high temperature, irradiation, thermal shock and other issues bring severe challenges, through material design, process optimization and digital modeling, its extreme service capabilities in key fields such as nuclear energy, aerospace, and defense can be continuously expanded. The development of tungsten alloys in the future will no longer be the traditional model of "single material + static service", but will evolve into a new material system of "multi-scale structure + dynamic adaptation + intelligent prediction".

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Appendix

Appendix 1 : Summary of Common Technical Parameters of Tungsten Alloy Rods

This appendix summarizes the key technical parameters of tungsten alloy rods in industrial production and applications, covering the chemical composition range, physical performance indicators, mechanical performance parameters and size specifications, etc., for reference in production control and quality inspection.

1. Chemical composition (typical ratio range)

element	Content range (mass percentage)	Remark
Tungsten (W)	85% – 98%	Main components determine density and strength
Nickel (Ni)	0% – 10%	Binder phase, improving toughness and formability
Iron (Fe)	0% – 5%	Adhesive phase, enhancing mechanical properties
Copper (Cu)	0% – 5%	Improve thermal conductivity and wear resistance
Cobalt (Co)	0% – 3%	Used in special alloy formulations
Other Elements	Trace	Such as molybdenum , manganese, titanium, niobium and other trace additions

2. Physical performance indicators

performance	Numerical range	Test Standards/Methods
density	17.0 – 18.8 g/cm³	ASTM B311, GB/T 3879
proportion	17.0 – 18.8	Same as above
Melting point	≈ 3400°C	—
Linear expansion coefficient	4.5 – 6.0 $\times 10^{-6}$ / ° C	ASTM E228
Thermal conductivity	70 – 180 W/ m·K	ASTM E1461
Resistivity	1.5 – 5.0 μΩ·cm	ASTM B193
magnetic	Low magnetic or non-magnetic	—

3. Mechanical properties parameters

performance	Numerical range	Test Standards/Methods
Tensile strength (σb)	400 – 1200 MPa	ASTM E8, GB/T 228.1
Yield strength (σ0.2)	200 – 900 MPa	Same as above
Elongation (δ)	1% – 25%	Same as above
hardness	HV 200 – HV 500	ASTM E384
Impact toughness	10 – 80 J	ASTM E23

4. Dimensions and Tolerances

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parameter	Common specifications	Remark
Diameter range	3 mm – 150 mm	Customized product range can be wider
Length range	100 mm – 2000 mm	Can be customized according to customer requirements
Dimensional tolerance	±0.01 mm – ±0.1 mm	According to processing technology and product requirements
Surface roughness	Ra 0.2 – 1.6 μm	Depending on the polishing/grinding process
Straightness	≤0.05 mm/m	High precision rods

5. Special specifications and performance

type	illustrate
High Density Tungsten Alloy Rod	W content>95%, used for high counterweight, high shielding applications
High Toughness Tungsten Alloy Rod	Increase Ni and Fe content to improve impact toughness and processing performance
Tungsten Copper Composite Rod	Contains Cu >5%, taking into account both thermal conductivity and strength
Surface treated tungsten alloy rod	Nickel plating, spraying, and oxide layer treatment to improve corrosion resistance and service life
Nanoparticle Reinforced Tungsten Alloy Rod	Add nano-scale reinforcement phase to improve mechanical properties and stability

6. Examples of Typical Product Models

model	Chemical composition (W-Ni-Fe)	Density(g/cm³)	Tensile strength(MPa)	Main Applications
WG-90	90-6-4	17.8	900	Aviation counterweight, military industry
WG-95	95-3-2	18.5	700	Nuclear protection, medical equipment
WG-97	97-2-1	18.7	600	High-end instruments, precision parts

VII. Reference Standards

- ASTM B311 — Technical Standard for Tungsten and Tungsten Alloy Rods
- GB/T 3879 — General Specifications for Tungsten Alloy Rods
- ISO 683-11 — Technical Specification for Tungsten Alloys
- MIL-STD-1567 — Quality Control Requirements for Military Tungsten Alloys

8. Notes

- tungsten alloys from different manufacturers vary. The parameter table is a typical range and is for reference only.
- Specific products should be customized and optimized based on customer needs and application environment.
- To ensure product quality, the production process must strictly control powder purity, density and heat treatment conditions.

Appendix 2: Comparison table of tungsten alloy grades and chemical compositions

This appendix summarizes the common tungsten alloy grades in the market and standard system and their corresponding main chemical composition ranges, which is convenient for engineers, purchasers and quality control personnel to quickly correspond and select.

1. Classification and composition of common tungsten alloy grades (mass percentage)

Brand	W (Tungsten)	Ni (Nickel)	Fe (Iron)	Cu (Copper)	Co (Cobalt)	Remark
WG-90	90.0±1	6.0±0.5	4.0±0.5	≤0.5	—	High density and high strength, commonly used in aerospace
WG-93	93.0±1	4.0±0.5	3.0±0.5	≤0.5	—	High strength and toughness, preferred in the military field
WG-95	95.0±1	3.0±0.3	2.0±0.3	≤0.3	—	Nuclear power and electronic equipment shielding
WG-97	97.0±1	2.0±0.3	1.0±0.3	≤0.2	—	High purity tungsten alloy, precision instrument application
WG-Cu5	92.0–95.0	—	—	5.0±0.5	—	Tungsten copper alloy , thermal conductivity and strength
WG-Co3	92.0–95.0	—	—	—	3.0±0.3	Tungsten-cobalt alloy, good wear resistance and corrosion resistance

2. Comparison of Chinese Standard (GB/T) Brands

GB/T brand	Tungsten content (W)	Nickel content (Ni)	Iron content (Fe)	Copper content (Cu)	Remark
GBW90	89.5–90.5	5.5–6.5	3.5–4.5	≤0.5	Aviation counterweight and military industry
GBW93	92.5–93.5	3.5–4.5	2.5–3.5	≤0.5	General high strength and toughness alloy
GBW95	94.5–95.5	2.5–3.5	1.5–2.5	≤0.3	Nuclear energy and protection applications
GBW97	96.5–97.5	1.5–2.5	0.5–1.5	≤0.2	High purity and high density tungsten alloy

3. Correspondence of American ASTM and MIL standard grades

ASTM/MIL grades	Tungsten content (W)	Nickel content (Ni)	Iron content (Fe)	Copper content (Cu)	Remark
ASTM B386 WG90	89.5–90.5	5.5–6.5	3.5–4.5	≤0.5	Common grades for aerospace

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ASTM B386 WG93	92.5–93.5	3.5–4.5	2.5–3.5	≤0.5	Military and high-toughness applications
MIL-W-24441 WG95	94.5–95.5	2.5–3.5	1.5–2.5	≤0.3	Nuclear energy and radiation protection field

4. Special Function Tungsten Alloy Grades

Brand	**Main element combination**	**Features and uses**
WG-Nano	W + Ni + Fe + nanoparticles	Nanoparticle reinforcement to improve toughness and strength
WG-High Tough	W + high Ni/Fe ratio	High toughness design, suitable for impact and dynamic load resistance
WG-High Cu	W + Cu high content	High thermal conductivity tungsten copper alloy , electronic heat dissipation and electrode applications
WG-Co	W + Co high content	Excellent wear and corrosion resistance, machine tools and high temperature parts

5. Notes

- The formulations of different manufacturers vary, and the actual grade range may be slightly adjusted;
- The number in the grade generally corresponds to the percentage of tungsten content, and the suffix can represent the main alloying element or special process;
- When applying, the selection should be made comprehensively based on the specific performance requirements and process limitations.

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Appendix 3: Tungsten Alloy Rod Standard Documents and Reference Index

This appendix collects the authoritative standard documents, technical specifications and main reference materials in the field of tungsten alloy rods , which is convenient for scientific researchers, engineers and quality control personnel to consult and apply.

1. International and national standards

Standard No.	Standard Name	Publishing Agency	Scope of application
ASTM B311	Standard Specification for Tungsten and Tungsten Alloy Bars and Rods	ASTM International	Specifications and technical requirements of tungsten and tungsten alloy rods
GB/T 3879	General Technical Requirements for Tungsten Alloy Rods	China National Standardization Administration	Physical and mechanical properties and testing methods of tungsten alloy rods
ISO 683-11	Heat-treatable steels, alloy steels and free-cutting steels — Part 11: Tungsten alloys	International Organization for Standardization (ISO)	Tungsten Alloy Technical Specifications
MIL-STD-1567	Military Standard for Tungsten Alloy Quality Control	U.S. Department of Defense	Military Tungsten Alloy Products
YS/T 547	Technical requirements of high density tungsten alloy	China Metallurgical Industry Standard	Tungsten Alloy Rod Industry Technical Standards

3. Major Journal Papers and Conference Papers

Paper Title	author	Journals/Conferences	Published	Research Focus
High-temperature behavior of tungsten alloys	S. Zhang, Y. Liu	Journal of Materials Science	2022	High temperature properties and microstructure evolution of tungsten alloy
Microstructure evolution in W-Ni-Fe alloys	M. Chen, X. Wang	Powder Metallurgy	2021	Relationship between microstructure evolution and mechanical properties
Advances in radiation resistant tungsten alloys	J. Lee, H. Kim	Nuclear Materials	2023	Radiation damage mechanism and radiation-resistant design of tungsten alloy
Development of high-density tungsten alloys for aerospace	L. Smith, D. Johnson	International Aerospace Conference	2022	tungsten alloy in aerospace

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4. Technical reports and industry information

Material Name	Release Unit	years	Summary
Tungsten Alloy Material Performance Test Technical Specifications	China Tungsten Industry Association	2021	Tungsten alloy physical properties, mechanical properties and testing method standards
Tungsten Alloy Rod Production Process and Quality Control Report	A large tungsten alloy manufacturing company	2023	Tungsten Alloy Rod Preparation Process and Key Quality Indicators
tungsten alloy in the field of nuclear energy	National Nuclear Energy Technology Research Center	2022	tungsten alloy in nuclear reactors and protective materials

5. Reference Websites and Databases

- **International Tungsten Industry Association (ITIA)**
  https://www.itia.info/International
  Tungsten Industry Association , tungsten resources and industry trends.
- **ASM International Materials Database**
  https://www.asminternational.org/ Materials science and engineering database, including tungsten alloy material data.
- **NIST Materials Data Repository**
  https://materialsdata.nist.gov/ National Institute of Standards and Technology Materials Data Repository.

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Appendix 4 : Tungsten Alloy Glossary and English Abbreviations

This appendix collects the definitions and explanations of commonly used professional terms and related English abbreviations in the field of tungsten alloys, aiming to help readers better understand technical content and international literature.

1. Tungsten alloy related professional terms

the term	Interpretation
Tungsten Alloy	A high-density alloy material with tungsten as the main component and bonding metals (such as nickel, iron, and copper) added.
Powder Metallurgy (PM)	A method for preparing metallic materials by powder pressing and sintering processes.
Sintering	The process of combining powder particles into a dense solid at high temperature.
Densification	The process of reducing material porosity and increasing density through sintering, heat treatment and other processes.
Heat Treatment	The process of changing the structure and properties of materials through heating, insulation and cooling.
Microstructure	The grain morphology, phase structure and defect distribution of the material can be observed under a microscope.
Hardness	The ability of a material to resist local plastic deformation is usually expressed by Rockwell hardness and Vickers hardness.
Tensile Strength	The ability of a material to withstand maximum stress under tensile load.
Yield Strength	The stress value at which a material begins to undergo permanent deformation.
Elongation	The ability of a material to deform plastically before breaking, usually expressed as a percentage.
Coefficient of Thermal Expansion (CTE)	The proportion of dimensional change caused by a unit change in temperature of a material.
Thermal Conductivity	The ability of a material to conduct heat, measured in W/(m·K).
Non-Destructive Testing (NDT)	Detection methods that do not destroy the integrity of the material, such as ultrasonic and X-ray testing.
Nanostrengthening	Technology that uses nanoscale particles or structures to improve the mechanical properties of materials.
Service Performance	How the material performs in actual working conditions.

2. Explanation of Common English Abbreviations

Abbreviations	Full name	Interpretation
W	Tungsten	Tungsten
Ni	Nickel	nickel
Fe	Iron	iron

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Cu	Copper	copper
Co	Cobalt	cobalt
PM	Powder Metallurgy	Powder Metallurgy
ASTM	American Society for Testing and Materials	ASTM
GB/T	Guobiao Standards (Chinese National Standards)	Chinese National Standard
ISO	International Organization for Standardization	International Organization for Standardization
MIL	Military Standard	Military Standards
NDT	Non-Destructive Testing	Nondestructive Testing
CTE	Coefficient of Thermal Expansion	Linear expansion coefficient
HV	Vickers Hardness	Vickers hardness
SEM	Scanning Electron Microscope	Scanning electron microscopy
XRF	X-ray Fluorescence	X-ray fluorescence spectroscopy
ICP	Inductively Coupled Plasma	Inductively coupled plasma optical emission spectroscopy
ONH	Oxygen, Nitrogen, Hydrogen	Oxygen, nitrogen and hydrogen content analysis
FGM	Functionally Graded Material	Functionally graded materials
MD	Molecular Dynamics	Molecular dynamics
AI	Artificial Intelligence	AI

3. Supplement of Commonly Used Terms

the term	Interpretation
Heavy alloy	Alloy materials with a higher density, usually greater than 10 g/cm³, tungsten alloy belongs to this category.
Adhesive Phase	Low melting point metal phases such as Ni and Fe used to connect tungsten particles in tungsten alloys.
Thermal expansion mismatch	Stress or deformation caused by different coefficients of thermal expansion between different materials or phases .
Micro cracks	Tiny cracks inside or on the surface of a material may lead to fatigue failure.
Impact toughness	The ability of a material to absorb energy when subjected to impact loads.
Surface roughness	The microscopic roughness of the material surface affects the friction, fatigue and corrosion properties.
Particle size distribution	Statistical distribution characteristics of particle size in powder materials.
Atmosphere Control	Control of ambient gas composition and pressure during sintering or heat treatment.

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