

# Tungsten Alloy Tube 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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[www.ctia.com.cn](http://www.ctia.com.cn)

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

## INTRODUCTION TO CTIA GROUP

CTIA GROUP LTD, a wholly-owned subsidiary with independent legal personality established by CHINATUNGSTEN ONLINE, is dedicated to promoting the intelligent, integrated, and flexible design and manufacturing of tungsten and molybdenum materials in the Industrial Internet era. CHINATUNGSTEN ONLINE, founded in 1997 with [www.chinatungsten.com](http://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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## CTIA GROUP LTD

### High-Density Tungsten Alloy Customization Service

CTIA GROUP LTD, a customization expert in high-density tungsten alloy design and production with 30 years of experience.

**Core advantages:** 30 years of experience: deeply familiar with tungsten alloy production, mature technology.

**Precision customization:** support high density (17-19 g/cm<sup>3</sup>), special performance, complex structure, super large and very small parts design and production.

**Quality cost:** optimized design, optimal mold and processing mode, excellent cost performance.

**Advanced capabilities:** advanced production equipment, RMI, ISO 9001 certification.

#### 100,000+ customers

Widely involved, covering aerospace, military industry, medical equipment, energy industry, sports and entertainment and other fields.

#### Service commitment

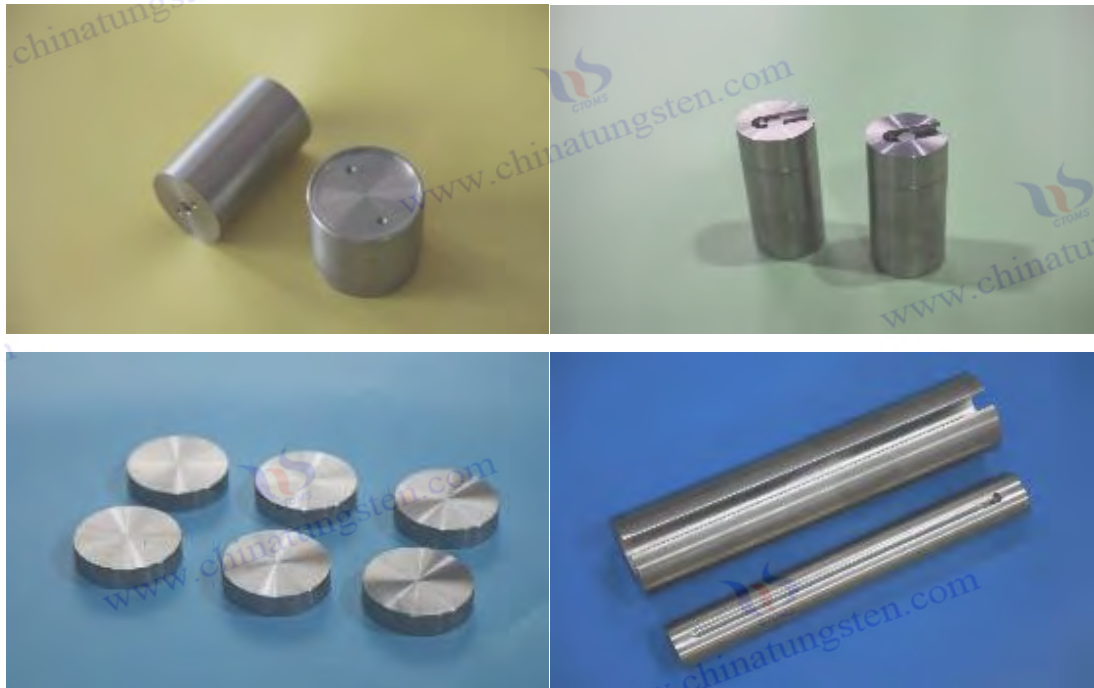
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Contact us

Email: [sales@chinatungsten.com](mailto:sales@chinatungsten.com)

Tel: +86 592 5129696

Official website: [www.tungsten-alloy.com](http://www.tungsten-alloy.com)



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## Table of Contents

### Chapter 1: Basic Concepts and Classification of Tungsten Alloy Tubes

- 1.1 Definition and Basic Structure of Tungsten Alloy Tubes
- 1.2 Introduction to the Material System of High-Specific-Gravity Tungsten Alloy Tubes (W-Ni-Fe / W-Ni-Cu)
- 1.3 Main Dimensional Parameters, Wall Thickness Range, and Standard Shapes of Tungsten Alloy Tubes
- 1.4 Classification of Tungsten Alloy Tubes (by Composition, Application, and Process)
- 1.5 Comparative Analysis of Tungsten Alloy Tubes with Tungsten Rods, Tungsten Plates, and Tungsten-Copper Tubes

### Chapter 2: Physical and Mechanical Properties of Tungsten Alloy Tubes

- 2.1 Density, Specific Gravity, and Dimensional Control Precision of Tungsten Alloy Tubes
- 2.2 Tensile Strength, Yield Strength, and Fracture Toughness of Tungsten Alloy Tubes
- 2.3 Hardness, Wear Resistance, and Impact Resistance of Tungsten Alloy Tubes
- 2.4 Thermal Conductivity, Thermal Expansion Coefficient, and High-Temperature Stability of Tungsten Alloy Tubes
- 2.5 Electrical Properties, Magnetic Response, and Radiation Resistance of Tungsten Alloy Tubes
- 2.6 Corrosion Resistance and Chemical Stability Analysis of Tungsten Alloy Tubes

### Chapter 3: Preparation and Forming Technology of Tungsten Alloy Tubes

- 3.1 Raw Material Preparation and Powder Property Analysis for Tungsten Alloy Tubes
- 3.2 Powder Metallurgy Pressing Technology for Tungsten Alloy Tubes (Molding, Isostatic Pressing)
- 3.3 Hollow Forming Process and Key Die Design for Tungsten Alloy Tubes
- 3.4 Sintering Technology and Atmosphere Control Optimization for Tungsten Alloy Tubes
- 3.5 Heat Treatment Process and Densification Enhancement Technology for Tungsten Alloy Tubes
- 3.6 Internal and External Surface Treatment of Tungsten Alloy Tubes (Polishing, Electroplating, PVD, etc.)
- 3.7 New Tungsten Alloy Tube Fabrication Technologies: Extrusion, Rolling, and Additive Manufacturing

### Chapter 4: Performance Testing and Quality Assessment of Tungsten Alloy Tubes

- 4.1 Tungsten Alloy Tube Appearance and Geometric Dimension Testing Methods
- 4.2 Tungsten Alloy Tube Density Testing and Microstructure Density Characterization
- 4.3 Tungsten Alloy Tube Mechanical Property Testing Standards (ASTM, GB, ISO)
- 4.4 Tungsten Alloy Tube Metallographic Analysis and Microstructural Observation
- 4.5 Tungsten Alloy Tube Chemical Composition and Impurity Testing (ICP, XRF, ONH)
- 4.6 Tungsten Alloy Tube Wall Thickness Uniformity and Coaxiality Assessment Methods
- 4.7 Tungsten Alloy Tube Surface and Internal Wall Defect Detection Techniques (Eddy Current, CT, Ultrasonic)

### Chapter 5: Typical Application Fields of Tungsten Alloy Tubes

- 5.1 Tungsten Alloy Tubes for Shielding and Structural Casing in the Nuclear Industry
- 5.2 Tungsten Alloy Tubes for Structural and Protective Functions in Military Weapon Systems
- 5.3 Tungsten Alloy Tubes for Protection and Positioning in Medical Radiotherapy Equipment

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5.4 Tungsten Alloy Tubes for Inertial Components and High-Temperature Flow Ducts in Aerospace

5.5 Tungsten Alloy Tubes for Heat Dissipation Ducts in Electronics and Communications Equipment

5.6 Tungsten Alloy Tubes for Structural Support in Industrial Molds and Wear-Resistant Liners

## **Chapter 6: Research and Development and Innovation Direction of Special Tungsten Alloy Tubes**

6.1 Preparation and Performance Optimization of Nanoparticle-Reinforced Tungsten Alloy Tubes

6.2 Design Strategies and Microstructure Control of Microalloyed Tungsten Alloy Tubes

6.3 Composite Electrical, Thermal, and Antimagnetic Properties of Multifunctional Tungsten Alloy Tubes

6.4 Microstructural Thermal Stability and Heat Treatment Paths of High-Temperature Tungsten Alloy Tubes

6.5 Study on the Interface Bonding Mechanism of W-Cu/W-Ni Composite Tungsten Alloy Tubes

6.6 Surface Coatings and Corrosion Resistance Enhancement Technologies for Functionalized Tungsten Alloy Tubes

## **Chapter 7: International Standards and Compliance System for Tungsten Alloy Tubes**

7.1 Chinese National/Industry Standards for Tungsten Alloy Tubes (GB/T, YS/T)

7.2 Interpretation of the US Standard System (ASTM, MIL) for Tungsten Alloy Tubes

7.3 EU and ISO International Standard Requirements for Tungsten Alloy Tubes

7.4 Environmental Compliance Requirements for Tungsten Alloy Tubes (RoHS, REACH, MSDS)

7.5 Quality Systems for Tungsten Alloy Tubes in Aviation, Nuclear Power, and Medical Applications (AS9100, ISO13485)

## **Chapter 8: Packaging, Storage, and Transportation Specifications for Tungsten Alloy Tubes**

8.1 Packaging Material Selection and Protection Design (Vacuum, Drying, Buffering) for Tungsten Alloy Tubes

8.2 Storage Conditions and Anti-Corrosion and Anti-Oxidation Requirements for Tungsten Alloy Tubes

8.3 International Transportation Specifications for Tungsten Alloy Tubes

8.4 Customs Supervision and License Application for Tungsten Alloy Tube Export

## **Chapter 9: Industrial Structure and Market Trend of Tungsten Alloy Tubes**

9.1 Global Tungsten Resource Overview and Tungsten Alloy Tube Industry Chain Analysis

9.2 Market Capacity and Demand Growth Trend Forecast for Tungsten Alloy Tubes

9.3 Introduction to CTIA GROUP Tungsten Alloy Tubes

9.4 Impact of Tungsten Alloy Tube Raw Material Price Fluctuations and Cost Structure

9.5 Emerging Demand and Policy Direction for Tungsten Alloy Tubes in High-End Manufacturing

9.6 Technical Barriers and Further Development Paths for the Tungsten Alloy Tube Industry

## **Chapter 10: Research Frontiers and Future Development of Tungsten Alloy Tubes**

10.1 Research on High Densification and Complex Shape Forming of Tungsten Alloy Tubes

10.2 Exploration of Additive Manufacturing Integration and Intelligent Manufacturing of Tungsten Alloy Tubes

10.3 Integrated Development and Application Expansion of Multifunctional Tungsten Alloy Composite Tubes

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10.4 Performance Evolution of Tungsten Alloy Tubes in Extreme Service Environments

10.5 Sustainable Development Strategies and Alternative Materials Research for Tungsten Alloy Tubes

## Appendix

Appendix 1: Common Physical/Mechanical Properties of Tungsten Alloy Tubes

Appendix 2: Comparison of Common Brands and Chemical Compositions of Tungsten Alloy Tubes

Appendix 3: Compilation of Relevant Standard Documents and Technical Data on Tungsten Alloy Tubes

Appendix 4: Tungsten Alloy Tube Glossary and English Abbreviations

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## Chapter 1 Basic Concepts and Classification of Tungsten Alloy Tubes

### 1.1 Definition and basic structure of tungsten alloy tube

Tungsten alloy tubes are an advanced functional structural material composed primarily of high-melting-point, high-density tungsten (W) alloyed with other metal elements such as nickel (Ni), iron (Fe), copper (Cu), and molybdenum (Mo) in specific proportions. These tubes are manufactured through powder metallurgy or other forming processes into hollow, cylindrical, or shaped tubes. Tungsten alloy tubes combine tungsten's high density and high-temperature stability with the ductility, machinability, and comprehensive physical properties imparted by the alloying elements. They are widely used in the nuclear industry, aerospace, military equipment, medical protection, electronic packaging, and high-temperature process systems.

#### 1. Define hierarchical parsing

From the perspective of composition structure, the core of tungsten alloy tube is composed of 90% to 98% tungsten. By forming a dense and uniform metal matrix with 1% to 10% of metal elements such as Ni, Fe, and Cu, it not only maintains the high specific gravity of tungsten (density can reach 17.0 to 18.5 g/cm<sup>3</sup>), but also obtains a certain degree of plasticity and machinability.

From a structural perspective, tungsten alloy tubes typically appear as hollow tubular products with circular or rectangular cross-sections. Their wall thickness, length, inner diameter, and outer diameter can be flexibly customized based on application requirements. Typical wall thicknesses range from 0.5 mm to 10 mm, and lengths can reach tens of centimeters or even meters. Depending

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on the operating environment, cross-sectional shapes can also be designed as elliptical, polygonal, or layered composite structures to meet stress distribution requirements under specific working conditions.

In terms of manufacturing methods, tungsten alloy tubes are primarily manufactured using powder metallurgy, which involves mixing tungsten-based powder with alloying elements in a proportional manner, pressing and forming the mixture, and then densifying and sintering it under a high-temperature protective atmosphere to form a highly dense, high-strength tungsten alloy billet. This is then machined, rolled, or extruded to create a hollow tube with the desired dimensions and surface accuracy. Furthermore, in recent years, advanced manufacturing processes such as cold isostatic pressing (CIP), hot isostatic pressing (HIP), and laser additive manufacturing have also been applied to the high-performance production of tungsten alloy tubes.

## 2. Structural characteristics and performance advantages

Tungsten alloy tubes have significant advantages in functional applications due to their tubular structure:

1. **Synergistic properties of high specific gravity and hollow design** : The high density of tungsten enables tungsten alloy tubes to achieve a large mass distribution in a small volume , making them particularly suitable for use as inertial parts, counterweight elements, radiation shielding sleeves, etc. The tubular structure helps to reduce the load on non-functional areas and improve the integration efficiency of the system.
2. **Good thermal and electrical properties** : Tungsten alloy tubes have excellent thermal stability and thermal conductivity at high temperatures, making them suitable for use as high-temperature fluid conduits, thermal field structures, and thermal shielding enclosures in vacuum devices. Furthermore, their low resistivity makes them useful in certain electromagnetic shielding, discharge devices, and electric heating elements.
3. **Strong controllability in structural processing** : Compared with pure tungsten, tungsten alloy has a certain degree of machinability while maintaining basic strength due to the introduction of alloying elements with better ductility. It can obtain high-precision inner and outer diameter dimensions and surface roughness through turning, inner diameter grinding, polishing, etc., meeting high-demand assembly needs.
4. **Strong radiation resistance, corrosion resistance, and fatigue resistance** : Tungsten alloy tubes are primarily used in high-radiation environments such as nuclear power plants and radiotherapy equipment. Their excellent shielding properties and structural stability make them a preferred material for neutron-absorbing sleeves and gamma-ray blocking components. Surface treatments (such as nickel plating and PVD coatings) can further enhance corrosion resistance and extend service life.

## 3. Structural Differences from a Classification Perspective

Tungsten alloy tubes often exhibit different characteristics in structural design according to different classification methods, such as:

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- **Classification by inner diameter/wall thickness ratio** : Thin-walled tungsten alloy tubes (wall thickness <1 mm) are mostly used in situations with strict quality and space requirements, such as aerospace inertial parts; thick-walled tungsten alloy tubes are used in pressure-bearing and impact-resistant environments, such as core jackets and pressure cylinders.
- **Classification by forming method** : molded type, hollow extrusion type, rolled welding type, etc., each corresponding to different dimensional accuracy and cost control capabilities.
- **Classification by application function** : structural support type (such as guide tubes, frame tubes), shielding and protection type (such as radiation protection covers), heat transfer and electrical conductivity type (such as high-temperature thermal field tubes), etc.

#### 4. Differences between tungsten alloy tubes and traditional tubes

Compared with traditional pipes such as stainless steel, copper alloy, and titanium alloy, tungsten alloy pipes are unique in the following aspects:

- Higher density, stronger radiation resistance, and can achieve the same or higher barrier effect with thinner tube walls;
- The high melting point (tungsten reaches 3410°C) gives it excellent high-temperature structural stability;
- Electromagnetic opacity makes it suitable for shielding and suppression structures in special bands;
- The structural strength is higher than that of titanium alloy, the wear resistance is better than that of copper alloy, and the corrosion resistance can be enhanced by coating.

#### V. Summary

In summary, tungsten alloy tubes are a type of hollow structural material that combines high density, high strength, excellent thermal stability, and functional diversity. Its definition is not limited to the form of a "tube," but also represents an engineering material system with extremely strong composite properties. With the continuous advancement of preparation technology and application requirements, the structural form and functional configuration of tungsten alloy tubes will continue to evolve, developing towards higher precision, lighter weight, and more integrated directions.

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

High - Density Tungsten Alloy Tube is a multiphase metal material composed of tungsten (W) as the main element (usually 85% to 98%) and supplemented by a certain proportion of nickel (Ni), iron (Fe) or copper (Cu). Due to its extremely high density (usually  $\geq 17.0 \text{ g/cm}^3$ ), excellent mechanical strength and good machinability, it is widely used in high-end fields such as protective structures, inertial components, radiation-resistant casings, and nuclear industry conduits.

Among tungsten alloy tube material systems, **W-Ni-Fe** and **W-Ni-Cu** are currently the two most popular high-density tungsten alloy systems. Through different element ratios and microstructure

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control methods, they achieve an organic balance of mechanical properties, electromagnetic properties, and service stability while maintaining high density.

## 1. Introduction to W-Ni-Fe System Tungsten Alloy Tube

### 1. System characteristics

W-Ni-Fe alloy systems typically consist of tungsten (90% to 97%) as the primary matrix, with nickel and iron forming the binder metal (typically Ni:Fe = 7:3 to 1:1). They exhibit a dual-phase or three-phase structure, with tungsten particles surrounded by a continuous matrix of  $\gamma$ -Ni-Fe alloy. This structure imparts **high strength, high ductility, and good machinability**.

### 2. Application advantages

- **High strength and high toughness** : Typical tensile strength can reach 800~1000 MPa, and elongation is between 10%~30%, suitable for structural components subjected to complex stress environments.
- **Excellent weldability and machinability** : Compared with pure tungsten materials, the W-Ni-Fe system has better processing performance, which is convenient for deep hole processing, internal and external circle polishing, and precision welding.
- **Strong radiation resistance** : The high tungsten content gives it excellent gamma ray and X-ray shielding capabilities, and is widely used in hollow structures, protective casings, thermal control channels, etc. in the nuclear industry.

### 3. Typical application scenarios

- Neutron absorption tubes of nuclear reactors and shielding sleeves of nuclear waste treatment equipment;
- Protective cylinder of medical radiotherapy machine ;
- High-density inertial sleeves or structural stabilizers in missiles or spacecraft.

## 2. Introduction to W-Ni-Cu System Tungsten Alloy Tube

### 1. System characteristics

The W-Ni-Cu system also uses tungsten as the primary component, supplemented by nickel and copper as a binder phase. The Cu/Ni ratio is typically controlled between 1:1 and 3:7. In this system, Cu replaces Fe as the secondary element, forming a **non-magnetic binder phase**. This typically results in a more uniform structure and better electrical and thermal conductivity.

### 2. Application advantages

- **Non-magnetic material system** : The iron-free structure makes it suitable for highly sensitive magnetic field environments, such as MRI, magnetic sensitive detection and other equipment.
- **Better electrical and thermal conductivity** : It has lower resistivity and higher thermal conductivity than the W-Ni-Fe system, and can play a significant role in electromagnetic shielding and heat conduction channels.

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- **Controllable density range** : The density control range is wide (16.5~18.0 g/cm³), which can be fine-tuned according to the requirements of different tube structures.

3. Typical application scenarios

- Thermal control channels for avionics packaging;
- Non-magnetic detector components for high energy physics equipment;
- Radiation shielding layer in high frequency equipment or microwave protection system.

3. Comparative Analysis of Two Major Systems (Applicable to Tungsten Alloy Tubes)

Comparison Dimension	W-Ni-Fe system	W-Ni-Cu system
Organizational Structure	Tungsten particles + Ni-Fe binder phase	Tungsten particles + Ni-Cu bonding phase
Strength/toughness	Higher (tensile strength 800~1000 MPa, elongation 15%~30%)	High (tensile strength 600~800 MPa, elongation 10%~20%)
Processing performance	Good, suitable for machining and welding	Better, especially suitable for precision forming and deep hole drilling
Electromagnetic properties	weak magnetism	Non-magnetic
Electrical and thermal conductivity	medium	Better
Application Directions	Structural load-bearing, protective pipelines, military structures	Medical shielding, electronic thermal control, magnetic control detection

4. Exploration of other material systems

In addition to W-Ni-Fe and W-Ni-Cu systems, the research on tungsten alloy tubes is also expanding to other multi-element alloy systems, including:

- **W-Ni-Co alloy tube** : used for corrosion-resistant structures in high temperature and high pressure environments;
- **W-Mo-Ni alloy tube** : fusion of molybdenum improves high temperature service performance;
- **Tungsten-molybdenum-nickel-iron composite tube** : multi-phase coexistence structure, with better thermal shock resistance and durability.

This type of multi-element controlled alloy system is being used in cutting-edge fields such as nuclear fusion devices and extreme environment protection components, and will become one of the important research directions in the field of tungsten alloy tubes in the future.

V. Summary

The W-Ni-Fe and W-Ni-Cu heavy alloy systems are the two mainstays of tungsten alloy tube

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production and application. The former focuses on strength and structural safety, making it suitable for heavy-duty applications such as military and nuclear power. The latter, known for its non-magnetic properties and excellent thermal and electrical conductivity, is widely used in electronics, medical, and precision engineering. Each possesses advantages in performance and application, forming a dual-engineered structure for the tungsten alloy tube material system. With the continuous advancement of technologies such as powder metallurgy, composite materials, and additive manufacturing, the material system of tungsten alloy tubes will also tend to be more diversified, intelligent, and functionally integrated to meet the more complex and changing industrial challenges.

### 1.3 Main Dimensional Parameters, Wall Thickness Range and Standard Shapes of Tungsten Alloy Tubes

Tungsten alloy tubes, as functional metal tubing with high density, strong structure, and corrosion resistance, are widely used in military, nuclear energy, medical, aerospace, and high-end equipment manufacturing. Because their use often requires extremely high structural precision, service stability, and process adaptability, dimensional control of tungsten alloy tubes becomes a core quality indicator. This section systematically explains the key dimensional parameters, wall thickness range, and standard shape characteristics of tungsten alloy tubes in actual production and engineering applications, aiming to provide a detailed basis for material design, selection, and standardized production.

#### 1. Definition and measurement methods of main dimensional parameters

tungsten alloy tubes are composed of the following key parameters:

1. **Outer Diameter (OD)** : refers to the maximum diameter of the outer circumference of the tungsten alloy tube, commonly used units are millimeters (mm) or inches (in).
2. **Inner Diameter (ID)** : refers to the diameter of the internal pore of the tungsten alloy tube, which is a key indicator affecting the fluid flux and penetration ability within the tube.
3. **Wall Thickness** : half of the difference between the outer diameter and the inner diameter. The wall thickness determines the structural strength, compressive strength and radiation resistance of the tungsten alloy tube.
4. **Length** : The axial dimension of the tungsten alloy tube, which can be divided into fixed lengths (such as 100 mm, 300 mm, 500 mm) and customized lengths according to needs.

Usually in product manufacturing or quality inspection, instruments such as **laser diameter gauges, internal diameter micrometers, ultrasonic thickness gauges, optical imaging measurement systems**, etc. are used to perform high-precision dimensional inspections to ensure that they meet design requirements.

#### 2. Common size specifications and standard range

According to industry practices and customer needs, the dimensional parameters of tungsten alloy tubes usually follow the following ranges:

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project	Common Ranges (Metric Units)	illustrate
outer diameter	$\phi 1 \text{ mm} \sim \phi 150 \text{ mm}$	Special applications can reach more than $\phi 200 \text{ mm}$
inner diameter	$\phi 0.5 \text{ mm} \sim \phi 145 \text{ mm}$	Ensure wall thickness $\geq 0.25 \text{ mm}$ , generally not less than 10% of the outer diameter
wall thickness	0.25 mm to 30 mm	Ultra-thin wall tubes are used for precision medical treatment, while thick wall tubes are suitable for protective structures.
length	10 mm to 2000 mm	Usually $\leq 500 \text{ mm}$ , long tubes need hot isostatic pressing support control
Wall thickness deviation	$\pm 0.01 \text{ mm}$ to $\pm 0.2 \text{ mm}$	Precision products adopt stricter tolerance standards

Tungsten alloy tubes for different purposes have different requirements for dimensional accuracy, for example:

- **Tungsten alloy tubes for radiotherapy** : The inner diameter tolerance is required to be no more than  $\pm 0.02 \text{ mm}$  to ensure the tightness of the plug-in structure;
- **Inertial weight tungsten alloy tube** : Usually focus on the consistency of total mass and wall thickness, and the outer diameter tolerance can be relaxed to  $\pm 0.1 \text{ mm}$ ;
- **Nuclear reactor components** : Focus on controlling inner wall roughness and axial straightness to avoid stress concentration during service.

### 3. Relationship between wall thickness design and usage requirements

tungsten alloy tube is not only related to its load-bearing capacity, but also affects the processing difficulty, cooling capacity, thermal conductivity and service life. Generally speaking:

- **Thin-walled structure (wall thickness  $< 1 \text{ mm}$ )** : Suitable for small medical equipment, microchannel cooling, precision flow guide and other fields. It is difficult to process but has excellent thermal control performance.
- **Mid-wall structure (1 mm  $\sim$  5 mm)** : The most common, suitable for multi-purpose use such as high-density counterweights, military ferrules, nuclear shielding components, etc., taking into account both strength and processability.
- **Thick-walled structures ( $> 5 \text{ mm}$ )** : mostly used in high-impact, corrosion-resistant, and high-radiation protection situations, such as missile tail compartments, nuclear waste packaging and other structures. Hot isostatic pressing is usually required to eliminate internal residual stress.

In actual design, the wall thickness needs to be determined comprehensively based on the following factors:

- Required strength and stiffness indicators;
- Maximum internal and external pressure difference;
- Heat transfer efficiency requirements;
- limited space constraints;

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- Material cost control.

#### 4. Standard Geometry of Tungsten Alloy Tube

Although the basic form of tungsten alloy tube is cylindrical tube, it can be shaped into various geometric structures according to different usage environments and processing methods:

##### 1. Standard round tube

- The most common type, suitable for all types of ferrule, flow-through, and coaxial structures.
- Good concentricity can be achieved by using rotary dies or isostatic pressing.

##### 2. Square tubes and special-shaped tubes

- It is often used in areas with strict structural combination and positioning requirements.
- The production process is relatively complicated, and the forming requires directional pressing of the mold.

##### 3. Multi-channel tungsten alloy tube

- A tube with porous structure for airflow distribution and microstructure support;
- It is often seen in high-energy physics experiments and nuclear equipment cooling systems.

##### 4. Functional tube with thread or positioning groove

- Facilitate subsequent assembly, connection or fastening;
- Most of them are customized structures.

#### 5. Dimensional Accuracy Standards and International Comparison

unified global product standard for tungsten alloy tubes , the following standard systems are often used for design or acceptance:

- **China:** GB/T 3874, YS/T 798 , etc.
- **United States:** ASTM B777, MIL-T-21014, etc .;
- **Europe/ISO:** ISO 2768, ISO 286 tolerance classes , etc.

According to actual needs, it can be divided into the following accuracy levels:

grade	Wall thickness tolerance	OD/ID tolerance	Applicable areas
Ordinary	±0.2 mm	±0.3 mm	Counterweight, general structural parts
Precision grade	±0.05 mm	±0.1 mm	Medical, nuclear shielding, aerospace inertial components
Ultra-precision grade	Within ±0.01 mm	Within ±0.02 mm	Laser instrument components, high-energy light source devices

#### tungsten alloy tubes in material processing and product application is their ability

to achieve extremely close dimensional tolerances and complex structural formations while maintaining extremely high density and strength . Proper selection of outer diameter, inner diameter, wall thickness, and length, along with appropriate forming and testing technologies, is fundamental

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to ensuring they meet engineering requirements. With the advancement of additive manufacturing , precision machining, and intelligent testing technologies, the synergy between dimensional standardization and personalized customization of tungsten alloy tubes will continue to improve, driving their in-depth application in high-end manufacturing and extreme service applications.

#### 1.4 Classification of Tungsten Alloy Tubes (by Composition, Application, and Process)

Tungsten alloy tubes, as a specialty tubing material with high density, high melting point, excellent mechanical strength, and good corrosion resistance, play a key role in various fields. To better meet various engineering applications, processing requirements, and material standards, tungsten alloy tubes are carefully classified into multiple types during production and use. These classification standards typically focus on **the alloy composition system, typical application areas, and manufacturing processes** to guide design selection, performance evaluation, and standardized production.

This section will systematically introduce the common classification methods of tungsten alloy tubes in engineering practice, providing a basic basis for performance comparison, technology selection and application matching in subsequent chapters.

##### 1. Classification by component system

According to the combination and proportion of metal elements, tungsten alloy tubes are mainly divided into the following categories:

##### 1. W-Ni-Fe Tungsten Alloy Tube (Tungsten-Nickel-Iron Tube)

- **Features** : High density, good toughness, and strong magnetic conductivity.
- **Typical ratio** : tungsten accounts for 90-97%, and the rest is Ni and Fe in a ratio of 7:3 or 1:1.
- **Application** : inertial counterweight, bulletproof insert, armor-piercing projectile, nuclear protection tube, etc.
- **Process adaptation** : Suitable for powder metallurgy + hot isostatic pressing (HIP) process.

##### 2. W-Ni-Cu Tungsten Alloy Tube (Tungsten-Nickel-Copper Tube)

- **Features** : non-magnetic, better conductivity than W-Ni-Fe, strong corrosion resistance.
- **Typical proportions** : 90–95% tungsten , 5–10% combined of Ni and Cu.
- **Applications** : X-ray equipment shielding, MRI compatible components, electronic heat pipe housings.
- **Process adaptability** : suitable for isostatic pressing and precision machining, with good surface treatment properties.

##### 3. W-Cu alloy tube (Tungsten-Copper Tube)

- **Features** : composite structure, high thermal conductivity, low thermal expansion coefficient.

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- **Application** : Used in high-frequency thermal control equipment, electrode protection sleeves, rocket nozzles, etc.
- **Process difficulties** : uneven structure, difficult hot working, and copper infiltration technology is commonly used for preparation.

#### 4. Rare earth or micro-alloyed tungsten alloy tubes

- **Added elements** : La, Y, Zr, Re, Ti and other trace added elements.
- **Strengthening effect** : Improve grain refinement, thermal fatigue resistance and high temperature strength.
- **Application** : Used in plasma equipment, extreme thermal field devices, and microstructure inner tubes.

## 2. Classification by purpose

Different industries have specific structural and performance requirements for tungsten alloy tubes, which can be divided into the following categories according to their uses:

### 1. Tungsten alloy tube for protection and shielding

- **Typical scenarios** : nuclear power plant neutron/gamma ray protection equipment, radiotherapy equipment, and X-ray casings.
- **Performance requirements** : high density, non-magnetic, and stable radiation absorption.
- **Representative alloys** : Mainly W-Ni-Cu system, some W-Cu alloys are also applicable.

### 2. Military and aerospace structural management

- **Typical applications** : armor-piercing projectile core casing, missile counterweight inner cavity, inertial gyroscope outer tube.
- **Performance requirements** : high strength, impact resistance, high specific gravity, and stability at high temperatures.
- **Representative alloys** : mainly W-Ni-Fe system, which has both structural and kinetic energy control capabilities.

### 3. Tungsten alloy tubes for electronic and thermal control devices

- **Typical applications** : thermionic tubes, heat pipes, microwave devices, discharge electrode tubes.
- **Performance focus** : high thermal conductivity, low thermal expansion, and good welding performance.
- **Alloy recommendation** : W-Cu and W-Ni-Cu non-magnetic tungsten alloy tubes are preferred.

### 4. Medical and high-precision structural pipes

- **Applications** : Tumor treatment cannulas, CT/X-ray scanners, precision ferrules.
- **Focus** : Extremely small tolerances on outer and inner diameters, non-magnetic, safe and non-toxic.

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- **Selection criteria** : W-Ni-Cu non-magnetic alloy or customized ultra-thin wall microtubes.

### 3. Classification by processing method

tungsten alloy tube directly affects its internal structure, mechanical properties and application range. Different processing methods are divided into the following categories:

#### 1. Powder Metallurgy Pressed Tungsten Alloy Tube

- **Process flow** : metal powder proportioning → mold pressing or isostatic pressing → high temperature sintering → finishing.
- **Advantages** : good density control, suitable for complex tube shapes, and strong flexibility in small batches.
- **Disadvantages** : limited structural density, difficult to process thin-walled and extra-long tubes.

#### 2. Spinning tungsten alloy tube

- **Applicable objects** : round tubes with medium length and uniform wall thickness.
- **Features** : Improves organizational consistency, enhances mechanical properties, and is suitable for military shell structures.

#### 3. Extrusion and hot rolling of tungsten alloy tubes

- **Process Overview** : Tungsten alloy billets are extruded or rolled into tubes in a heated state .
- **Advantages** : high efficiency, stable tube shape, suitable for standardized mass production.
- **Limitations** : High equipment cost and high requirements on material plasticity.

#### 4. Additive Manufacturing (AM) Tungsten Alloy Tube

- **Technical means** : selective laser melting (SLM), electron beam melting (EBM), etc.
- **Innovative applications** : complex geometric structures (such as multi-lumen tubes) and gradient components can be realized.
- **Prospects** : Suitable for extreme working conditions and personalized high-end equipment applications.

### IV. Summary

tungsten alloy tubes reflects the highly customized nature of their material design, diverse application scenarios, and specialized manufacturing processes. Classification by composition facilitates precise matching of required performance; classification by application clarifies end-use objectives; and classification by process reflects production adaptability and technical capabilities. In the future, with the in-depth development of functional tungsten alloys and the widespread application of intelligent manufacturing technologies, the classification system for tungsten alloy tubes will become even more refined, providing high-performance, highly reliable metal tube solutions for various advanced projects.

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## 1.5 Comparative Analysis of Tungsten Alloy Tubes with Tungsten Rods, Tungsten Plates, Tungsten Copper Tubes and Other Materials

Tungsten and its alloy products, due to their excellent physical, mechanical, and chemical properties, hold a vital position in key sectors such as high-end equipment manufacturing, nuclear energy, aerospace, medical, and military applications. Among the numerous tungsten-based materials, tungsten alloy tubes, rods, plates, and tungsten copper tubes are the most common. These materials share similarities in structure, function, performance, and processing, yet each possesses distinct characteristics.

This section will systematically compare tungsten alloy tubes with the above-mentioned materials to help designers, material selection engineers and manufacturers make more scientific material matching and substitution judgments.

### 1. Comparison of structural morphology

Material name	Basic form	Typical structure description
<b>Tungsten Alloy Tube</b>	Hollow cylinder, special-shaped multi-cavity body	Outer diameter, inner diameter and wall thickness are key parameters
<b>Tungsten rod</b>	Solid cylinder	Commonly used for diameter control, flexible length customization
<b>Tungsten Plate</b>	Solid flat plate	Width × length × thickness control, suitable for paving structures
<b>Tungsten copper tube</b>	Copper-clad tungsten composite hollow structure	Usually W-Cu composite, thermal conductivity is better than tungsten alloy tube

tungsten alloy tubes is that they are “hollow”. This hollow feature gives them irreplaceable advantages in scenarios such as quality control, thermal management, media channels, and protective sleeves.

### 2. Performance Parameter Comparison

project	Tungsten Alloy Tube	Tungsten rod	Tungsten Plate	Tungsten copper tube
<b>density</b>	17.0–18.8 g/cm <sup>3</sup>	18.0–19.2 g/cm <sup>3</sup>	18.0–19.2 g/cm <sup>3</sup>	14.5–17.0 g/cm <sup>3</sup>
<b>Strength and toughness</b>	High strength, medium toughness	High strength and high rigidity	High stiffness, low toughness	Medium strength, excellent thermal conductivity
<b>Thermal conductivity</b>	medium	Low to medium	Low to medium	High (>200 W/ m·K )
<b>Conductivity</b>	generally	generally	generally	High (for spark discharge only)
<b>Non-magnetic</b>	tungsten nickel copper system available	Mostly magnetic	Mostly magnetic	Non-magnetic

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<b>Radiation resistance</b>	Very strong	Very strong	Very strong	powerful
<b>Shape complexity support</b>	High (can be made into special-shaped multi-lumen tubes)	generally	generally	generally

Tungsten alloy tubes excel in comprehensive strength, lightweight size, and radiation protection, and are particularly suitable for special scenarios requiring **hollow structures** or **weight-optimized designs**.

### 3. Processing technology comparison

Material name	Forming method	Processing difficulty	Secondary processing method
<b>Tungsten Alloy Tube</b>	Powder metallurgy, isostatic pressing, spinning, etc.	High (especially thin-walled tubes)	Internal and external grinding, fine turning, surface polishing
<b>Tungsten rod</b>	Powder pressing, sintering, forging	Lower	Cutting, grinding, rolling
<b>Tungsten Plate</b>	Hot rolled or cold rolled, sintered plates	medium	Cutting, laser forming, welding
<b>Tungsten copper tube</b>	Copper infiltration, extrusion or powder injection	Higher	Electrode processing, heat treatment, welding

Tungsten alloy tubes are generally more difficult to process than solid structures such as tungsten rods and plates due to their hollow structure and high-density material. Especially in the design of precise inner holes and extremely thin walls, extremely high requirements are placed on equipment and processes.

### 4. Comparison of usage scenarios

Application Areas	Tungsten Alloy Tube	Tungsten rod	Tungsten Plate	Tungsten copper tube
<b>military industry</b>	Armor-piercing shell, missile tail compartment inner tube	Core, counterweight rod	Protective armor	Muzzle electrode, heat exchange sleeve
<b>nuclear energy</b>	Neutron absorption tubes, nuclear waste coating tubes	Control rods, shielding blocks	Reflective screen, furnace wall	Cooling jacket
<b>Medical</b>	Radiotherapy sleeve, gamma knife collimator	counterweight rod	X-ray shield	Electromagnetic wave transparent tube
<b>Electronics and Thermal Control</b>	Heat pipe shell, laser device tube	Heat source core	Microwave absorption plate	High frequency electrodes, heat diffusers
<b>Aerospace</b>	Satellite attitude control inertial weight tube, thruster high temperature cavity	Gyro flywheel rod	Aerospace radiation shielding panels	Thermal control plate, electrode kit

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Tungsten alloy tubes are more suitable for application scenarios that require a balance between strength and mass ratio, symmetrical inertial structures, heat transfer channels or radiation protection shells, showing their irreplaceable engineering advantages.

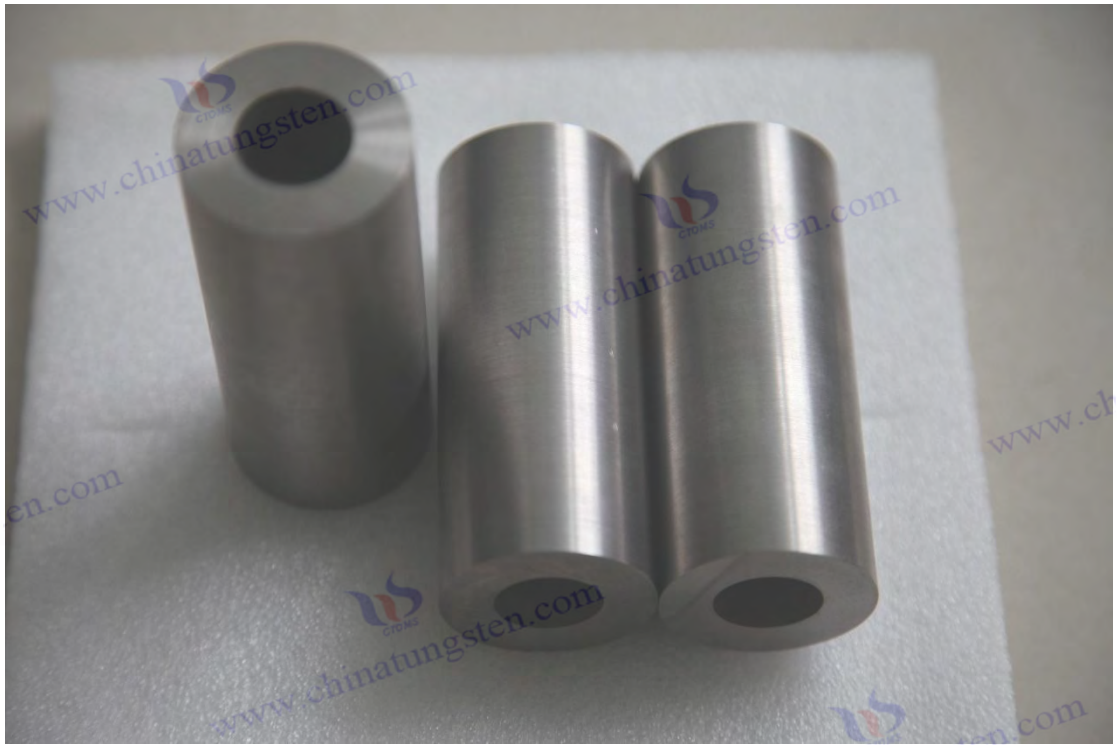
## V. Summary

tungsten alloy tubes share the same tungsten-based material system as tungsten rods, tungsten plates, and tungsten-copper tubes in terms of fundamental performance , they differ significantly in structural design, usage, and process paths. Due to their unique hollow, high-strength structure, tungsten alloy tubes offer greater application flexibility in terms of **high specific gravity, non-magnetic properties, protective and flow-guiding properties, and precise fit** . The trend toward lightweighting and multifunctional tungsten alloy tubes is particularly prominent in the nuclear energy, aviation, and military sectors.

Understanding the similarities and differences between different tungsten-based materials not only helps with efficient selection, but also improves the innovation and reliability of product structural design.

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Chapter 2 Physical and Mechanical Properties of Tungsten Alloy Tube

2.1 Density, specific gravity and dimensional control accuracy of tungsten alloy tubes

As an engineering material with high specific gravity, high temperature resistance, and structural stability, tungsten alloy tubes' physical properties directly determine their performance in key applications such as high-end equipment manufacturing, nuclear power protection, aerospace, and precision instruments. **Density, specific gravity, and dimensional control accuracy** are key indicators for evaluating the quality and performance of tungsten alloy tubes.

1. Density and specific gravity range of tungsten alloy tube

tungsten alloy tubes is generally between **16.8 and 18.8 g/cm³** , depending on the composition of the alloy system, density level and forming process. Typical alloy systems are as follows:

Alloy type	Main components (mass percentage)	Theoretical density (g/cm³)
W-Ni-Fe series	W ≈ 90–97%, Ni ≈ 2–7%, Fe ≈ 1–3%	17.5–18.5
W-Ni-Cu series	W ≈ 85–95%, Ni/Cu ≈ 5–15%	17.0–18.3
High-density W composite system	W > 97%, other metals added in small amounts	18.8 and above

Density is a key indicator of densification and material uniformity. Tungsten alloy tubes are manufactured using a powder metallurgy pressing and sintering process. The final density is

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influenced by factors such as powder particle size, pressing method (cold isostatic pressing or die pressing), sintering atmosphere, and temperature control. Microporosity and uneven compaction can significantly impact density, particularly in tungsten alloy tubes with thin inner walls or large dimensions, necessitating optimization through hot isostatic pressing (HIP) or densification.

### Specific Gravity Characteristics and Engineering Significance of Tungsten Alloy Tubes:

"Specific gravity" is a relative measure of density, defined as the ratio of a material's density to the density of water (at 4°C). Tungsten alloy tubes typically have a specific gravity between **17.0 and 18.8**, making them a heavy metal alloy. Their high specific gravity provides the following key engineering advantages:

- **Inertial weight increase** : In aircraft counterweights and gyro components, it can effectively increase system inertia and improve stability.
- **High space utilization efficiency** : Compared with other protective materials (such as steel and lead), it can achieve the same or even higher protection or structural load in a smaller volume.
- **Excellent anti-vibration and energy absorption performance** : The material with higher specific gravity has stronger kinetic energy damping and absorption capacity, suitable for bulletproof and impact-proof applications.

### 3. Dimension Control and Processing Accuracy of Tungsten Alloy Tube

The dimensional control accuracy of tungsten alloy tubes is mainly reflected in the following key parameters:

- **Outer diameter tolerance** : usually controlled within  $\pm 0.01$  mm to  $\pm 0.05$  mm, depending on product specifications;
- **Inner diameter tolerance** : Affected by sintering shrinkage and machining, the tolerance is generally within the range of  $\pm 0.02$  mm to  $\pm 0.10$  mm;
- **Wall thickness uniformity** : It is an important guarantee for structural integrity. High-precision products require that the wall thickness difference does not exceed  $\pm 5\%$ ;
- **Straightness and roundness** : Especially in long tube products, straightness control to within 0.1 mm/m is the aviation/military standard.

Tungsten alloy has high hardness, great brittleness and high processing difficulty. The accuracy of processing dimensions must be guaranteed by the following process means:

- **High-precision mold pressing** ensures uniform initial shape and size;
- **Uniform temperature control during high-temperature sintering** to avoid uneven sintering shrinkage;
- **Secondary precision turning, internal and external grinding**, ultimately obtaining precise inner holes and smooth outer walls;
- **Non-contact laser/optical measurement systems** are used for full or spot inspection of finished product dimensions.

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#### 4. Impact of Dimensional Control on Service Performance

Dimensional control accuracy plays a decisive role in the service stability of tungsten alloy tubes:

- **Precision inner diameter** : affects the efficiency of fluid channels, gamma ray focusers, heat exchangers, etc.
- **Wall thickness consistency** : related to thermal stress distribution, protection uniformity and structural strength;
- **Shape error control** : can improve the overall stability of the system in component assembly and multi-tube parallel structure;
- **Dimensional stability** : Preserving dimensions in high temperature and high pressure environments is the key to ensuring long service life.

Therefore, tungsten alloy tubes not only require high density and no internal defects, but also need to achieve strict control of geometric dimensions and shapes to meet the requirements of precise adaptation and high reliability in complex environments.

#### V. Summary

Tungsten alloy tubes, with their high density, high specific gravity, and exceptional dimensional precision, have become irreplaceable core structural components in numerous high-end fields. Currently, with the advancement of isostatic pressing, high-precision mold design, CNC grinding, and non-contact inspection technologies, dimensional control of tungsten alloy tubes is steadily advancing toward submicron tolerances. Future applications in nuclear medicine, ultra-high-temperature energy systems, and extreme service equipment will be even more promising.

#### 2.2 Tensile Strength, Yield Strength and Fracture Toughness of Tungsten Alloy Tube

Tungsten alloy tubes, due to their high density, high melting point, and excellent mechanical properties, play an important role in aerospace, nuclear shielding, military protection, and high-end equipment manufacturing. Tensile strength, yield strength, and fracture toughness are key mechanical indicators for evaluating their structural stability and service reliability.

##### 1. Overview of tensile strength and yield strength

- **Tensile strength ( $\sigma_b$ )** : It is the maximum stress that a material can withstand in a tensile test, indicating the ultimate tensile force that the material can withstand before breaking.
- **Yield strength ( $\sigma_s$ )** : refers to the stress point at which the material begins to undergo obvious plastic deformation and is the standard for judging the elastic limit of the material.

tungsten alloy tubes, such as W-Ni-Fe and W-Ni-Cu, have tensile strength and yield strength that are closely related to alloy composition, microstructure, densification degree, and subsequent heat treatment.

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Alloy system	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
W-Ni-Fe (90W)	700–1000	500–800	10–25
W-Ni-Cu (90W)	600–900	400–700	15–30
High-strength W alloy	1000–1200+	800–1000	5–15

## 2. Influence of alloy design on strength properties

1. **tungsten content** : Increased high-temperature strength and specific gravity, but decreased plasticity;
2. **Adjustment of Ni/Fe ratio** : Improvement of phase boundary bonding ability and solid solution strengthening degree;
3. **Grain size refinement** : Grain refinement can increase yield strength but may reduce ductility;
4. **Sintering densification and heat treatment** : can reduce internal porosity, improve strength and structural consistency.

For example, after using the **\*\*hot isostatic pressing (HIP)\*\*** process, the density of tungsten alloy tubes can reach more than 99.5%, and the yield strength can be increased by 15%~20%.

## 3. Fracture toughness and its evaluation

**Fracture toughness (KIC)** refers to a material's ability to resist crack propagation in the presence of defects or cracks, reflecting its ability to withstand brittle fracture. For materials such as tungsten alloy tubes, which operate in complex stress fields, fracture toughness is of vital engineering significance.

tungsten alloys is typically in the range of 15–35 MPa·m<sup>1/2</sup>, which is much higher than that of pure tungsten (<10 MPa·m<sup>1/2</sup>). Its performance is affected by the following factors:

- **Tough phase content (Ni/Cu)** : The tough metal matrix provides a channel for crack passivation and energy dissipation;
- **Multiphase interface distribution** : Dispersion-strengthened particles and discontinuous structures can hinder crack propagation;
- **Microcrack absorption mechanism** : conducive to the formation of a buffer zone at the crack tip.

Improvement measures include: adding rare earth elements (such as La and Ce) through microalloying, or achieving "strong-tough" synergy through dual-phase structure design.

## 4. Effect of temperature on strength properties

tungsten alloy tubes is sensitive to temperature:

- In the range of **600–800°C** , the tensile strength remains relatively stable;
- Above **1000°C** , some alloy systems will experience a decrease in strength due to grain boundary weakening, phase precipitation, and other phenomena;

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- Some high-temperature resistant W alloy systems (such as W-Re-Ni-Fe) can still maintain a strength of more than 500 MPa in the range of **1200–1500°C** .

Therefore, for tungsten alloy tubes under high-temperature service conditions, it is necessary to combine heat treatment strengthening and microstructure control strategies to delay performance degradation.

5. Comparison of strength requirements in typical application scenarios

Application Areas	Typical strength requirements (MPa)	illustrate
Aerospace thrust accessories	>900	Withstand high-speed rotation/impact/temperature difference
Military armor-piercing/kinetic energy components	800–1000	High impact strength and stable inertia output
Nuclear shielding components	600–800	Balanced strength and toughness, resistant to radiation/thermal fatigue
Medical high-density equipment (radiotherapy)	500–700	Stable support/shielding, no ultimate strength required

VI. Summary

tungsten alloy tubes demonstrate their core competitiveness as a "heavy-duty structural functional composite material." Supported by multi-dimensional technologies such as alloy system optimization, powder metallurgy densification control, heat treatment regulation, and microstructure design, modern tungsten alloy tubes now combine **high strength and machinability** , meeting the demanding requirements of key industries such as nuclear, aerospace, military, and medicine.

2.3 Hardness, wear resistance and impact resistance of tungsten alloy tube

Tungsten alloy tubes, due to their high density and excellent mechanical properties, are widely used in aerospace, nuclear protection, military equipment fittings, and high-end machinery manufacturing. Hardness, wear resistance, and impact resistance are important indicators for evaluating the performance of tungsten alloy tubes in actual working conditions, directly affecting their service life, safety, and reliability.

1. Hardness Characteristics of Tungsten Alloy Tube

Hardness reflects a material's ability to resist local plastic deformation and is an important indicator of the wear resistance and load-bearing performance of tungsten alloy tubes . The hardness of tungsten alloy tubes is primarily affected by the alloy composition, preparation process, and heat treatment process.

- **Hardness types and measurement methods**  
are commonly measured using Rockwell hardness (HRC), Vickers hardness (HV), and

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Brinell hardness (HB). The typical hardness range for W-Ni-Fe tungsten alloy tubes is HV250–450 , equivalent to HRC30–45 .

- **Factors affecting hardness**

1. **Tungsten content** : High tungsten content generally increases hardness, as tungsten itself is extremely hard and rigid.
2. **Metal bonding phase ratio** : If the ratio of toughness phases such as Ni and Fe is too high, the overall hardness will be reduced, but it will be beneficial to improve toughness.
3. **Heat treatment and cold working** : Appropriate heat treatment can refine and strengthen the structure and improve the hardness; cold working can introduce dislocation density and further increase the hardness value.
4. **Microstructure morphology** : Uniform and fine grains and dense non-porous structure help to improve hardness.

## 2. Wear resistance of tungsten alloy tube

Tungsten alloy tubes exhibit excellent wear resistance in high-abrasion environments and are suitable for applications subject to mechanical friction, impact, and wear.

- **Wear resistance mechanism**

1. **Dispersion strengthening of high hardness phase** : The tungsten phase particles in tungsten alloy have high hardness and effectively resist surface wear.
2. **Toughness support of metal matrix** : Nickel and iron matrix provide a certain plasticity to buffer external forces and prevent the material from cracking and peeling.
3. **Surface density** : The dense and non-porous material structure effectively reduces the intrusion of abrasive particles and corrosive media, extending the service life.

- **Wear resistance evaluation index**

- **Wear rate ( $\text{mg}/\text{cm}^2/\text{h}$  or  $\text{mm}^3/\text{N}\cdot\text{m}$ )**
- **Wear coefficient**
- **Friction coefficient**

- **Experimental research data example:**

W-Ni-Fe tungsten alloy tubes exhibit a low wear rate in grinding wheel wear tests, approximately 1/5 of that of ordinary steel, demonstrating extremely strong wear resistance.

## 3. Impact resistance of tungsten alloy tube

Impact resistance is the ability of a material to resist sudden loads or dynamic impact damage, which is directly related to the safety and reliability of tungsten alloy tubes under complex working conditions.

- **Key factors for impact resistance of tungsten alloy tubes**

1. **Matrix toughness** : Ni and Fe act as metal bonding phases, providing plastic deformation capability and dispersing stress concentration.
2. **Microstructure uniformity** : Uniform grain size and phase interface reduce crack initiation points and improve impact toughness.

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3. **Densification degree** : High density reduces defects such as holes and cracks, effectively improving impact resistance.
4. **Strengthening effect of added elements** : Microalloying elements such as titanium and niobium can refine grains and improve toughness.

- **Test Method**

- **Impact tests** ( such as the Charpy impact test ) measure the impact energy absorbed (J)
- **Dynamic fatigue testing** examines the failure characteristics of materials under cyclic impact

- **Typical Performance Data:**

The Charpy impact toughness of standard W-Ni-Fe tungsten alloy tubes is generally between **5 and 15 J/cm<sup>2</sup>** . **High-toughness alloys can be increased to over 20 J/cm<sup>2</sup>** through heat treatment and microalloying .

#### 4. Synergistic optimization of hardness, wear resistance and impact resistance

tungsten alloy tubes, hardness, wear resistance and impact resistance often need to achieve an optimal balance to avoid increased brittleness due to excessive hardness, or increased toughness at the expense of wear resistance.

- **Alloy design strategy**

1. By adjusting the ratio of W and Ni/Fe, both hardness and toughness can be achieved.
2. The introduction of nanoparticles and microalloying technology can refine grains and improve overall mechanical properties.
3. Composite surface coating technology (such as TiN , CrN , etc.) is used to improve surface hardness and wear resistance while protecting the toughness of the substrate.

- **Process Control**

Precisely control powder particle size distribution, compacting pressure, and sintering process to reduce inherent defects and improve density and performance consistency.

#### 5. Application Examples

- **Aerospace high-strength pipes** : The material requires both high hardness and impact resistance. Tungsten alloy pipes provide excellent mechanical protection and dimensional stability.
- **Nuclear protection pipes** : exhibit excellent wear resistance and structural toughness in high-radiation environments, ensuring equipment safety.
- **Military armor-piercing casing** : Hardness and wear resistance are key factors in ensuring armor-piercing effect and structural integrity.

#### VI. Summary

tungsten alloy tubes are their core competitive advantages in a wide range of applications. Through scientific material design and advanced manufacturing processes, tungsten alloy tubes achieve an

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optimal combination of hardness and toughness, extending service life and safety while meeting demanding service conditions.

## 2.4 Thermal conductivity, thermal expansion coefficient and high temperature stability of tungsten alloy tubes

tungsten alloy tubes play a key role in numerous high-temperature and extreme working conditions. Their thermal conductivity, thermal expansion coefficient, and high-temperature stability directly impact their structural stability and service life, making them particularly important in aerospace, nuclear industry, and high-temperature furnace tubes.

### 1. Thermal conductivity of tungsten alloy tube

Thermal conductivity refers to the ability of a material to conduct heat energy. High thermal conductivity helps to dissipate heat quickly and avoid material damage caused by local overheating.

- Pure tungsten has an extremely high thermal conductivity of approximately  $170 \text{ W}/(\text{m}\cdot\text{K})$ . However, the addition of binder phases such as nickel and iron to tungsten alloys reduces this thermal conductivity. Typical W-Ni-Fe **tungsten alloy tubes** have a thermal conductivity of approximately  $50\text{--}70 \text{ W}/(\text{m}\cdot\text{K})$ , still significantly higher than most metals.
- **Influencing factors**
  1. **Composition ratio** : The higher the tungsten content, the better the thermal conductivity; the greater the binder phase content, the lower the thermal conductivity.
  2. **Microstructure and density** : Dense, fine-grained and non-porous structure is conducive to heat conduction.
  3. **Temperature** : Thermal conductivity generally decreases as temperature increases, but tungsten alloy still maintains good thermal conductivity.
- **Application significance:**

High thermal conductivity makes tungsten alloy tubes suitable for high-temperature heat exchangers, heat dissipation pipes and electronic device cooling systems to ensure thermally stable operation of equipment.

### 2. Thermal Expansion Coefficient of Tungsten Alloy Tube

The coefficient of thermal expansion reflects the property of a material's dimensional change due to temperature changes and is an important parameter that must be considered when designing high-temperature structural parts.

- **The**

linear expansion coefficient of tungsten alloy tubes is typically in the range of  $4.5\times 10^{-6} / \text{K}$  to  $6.5\times 10^{-6} / \text{K}$  (room temperature to approximately  $800^{\circ}\text{C}$ ). This value is lower than that of most steel materials, indicating good dimensional stability.
- **Influencing factors**

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1. **Alloy composition** : The low thermal expansion properties of tungsten and molybdenum dominate the overall performance, while metal binder phases such as Ni and Fe slightly increase the thermal expansion coefficient.
2. **Microstructure** : Uniform grain structure and dense structure reduce local uneven thermal expansion and contraction.
3. **Heat treatment status** : Reasonable heat treatment helps to release internal stress and reduce thermal expansion deformation.

- **Engineering Application Considerations**

The low thermal expansion coefficient enables tungsten alloy tubes to maintain dimensional stability in high temperature environments, avoiding thermal stress cracks and deformation, and is particularly suitable for precision high-temperature pipelines and mechanical components.

### 3. High Temperature Stability of Tungsten Alloy Tube

High temperature stability refers to the ability of a material to maintain its physical, mechanical properties and chemical structure under high temperature conditions. It is the key to evaluating whether tungsten alloy tubes can work in extreme environments for a long time.

- **Thermal stability performance**

1. **High melting point advantage** : The melting point of tungsten is as high as 3422°C, and tungsten alloy tubes have extremely high high temperature resistance.
2. **Oxidation resistance** : Pure tungsten easily forms an oxide layer in a high-temperature oxidizing environment. Tungsten alloy tubes improve their oxidation resistance through composition control and surface coating technology.
3. **Mechanical properties maintenance** : Tungsten alloy tubes can maintain high strength and hardness at high temperatures to ensure structural stability.

- **Influencing factors**

1. **Alloy design** : Appropriate amounts of Ni, Fe and micro-alloying elements such as titanium and niobium improve high temperature performance and oxidation resistance.
2. **Surface treatment** : oxidation coating, ceramic coating, etc. to enhance surface protection.
3. **Operating environment** : The performance in vacuum and high-purity argon environment is better than that in oxygen-rich environment.

- **Application Cases**

Tungsten alloy tubes show excellent thermal stability in high-temperature furnace pipes, aircraft engine turbine cooling tubes, and nuclear reactor high-temperature structural parts.

### 4. Comprehensive Thermal Performance Optimization Strategy of Tungsten Alloy Tube

In order to improve the performance of tungsten alloy tubes in extreme high temperature environments, the following optimization methods are usually used:

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- **The material design**  
combines high tungsten content with an appropriate binder phase ratio to achieve a balance of high thermal conductivity and low thermal expansion.
- **Microstructure regulation**  
refines grains, reduces pores, and optimizes sintering and heat treatment processes.
- **Surface technology**  
uses anti-oxidation coating to extend service life.
- **Environmentally adaptable**  
design adapts to alloy systems in different high-temperature environments to meet different industrial needs.

## V. Summary

Tungsten alloy tubing, with its excellent thermal conductivity, low coefficient of thermal expansion, and exceptional high-temperature stability, has become an irreplaceable key material for high-temperature environments. Scientific composition design and process optimization can further enhance its comprehensive thermal performance, meeting the stringent requirements for high-performance tubing in fields such as aerospace, nuclear industry, and high-temperature machinery manufacturing.

## 2.5 Electrical Properties, Magnetic Response, and Radiation Resistance of Tungsten Alloy Tubes

Tungsten alloy tubes are widely used in modern high-tech fields due to their excellent electrical properties, magnetic response characteristics, and radiation resistance, especially in the nuclear industry, aerospace, and electronic equipment. A deep understanding and optimization of these properties is crucial to ensuring the stable operation of tungsten alloy tubes in extreme environments.

### 1. Electrical Properties of Tungsten Alloy Tube

- **Conductivity and resistivity**  
Since tungsten metal itself has good electrical conductivity, the resistivity of pure tungsten is about  $5.6 \times 10^{-8} \Omega \cdot m$ . However, tungsten alloy tubes are usually doped with nickel, iron and other binder phases. These elements have high resistivity, resulting in the overall conductivity of tungsten alloy tubes being lower than that of pure tungsten, generally between  $10^{-7}$  and  $10^{-6}$ . In the range of  $\Omega \cdot m$ .
- **Influencing factors**
  1. **Composition ratio** : the higher the tungsten content, the better the conductivity; the greater the binder phase content, the higher the resistivity.
  2. **Microstructure** : Dense and non-porous structure is conducive to electron conduction, while pores or cracks will significantly increase resistance.
  3. **Temperature effect** : Resistivity increases with increasing temperature. Special attention should be paid to the resistance change of tungsten alloy tubes in high temperature environments.

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- **Application significance**

Tungsten alloy tubes are suitable for high-temperature electronic equipment and electrode materials that require certain electrical conductivity. They also play an important role in the field of electromagnetic shielding.

## 2. Magnetic response characteristics of tungsten alloy tube

- **is**

a paramagnetic metal with a weak magnetic response, but the ferromagnetic elements such as iron and nickel doped in the alloy will enhance the overall magnetic properties, making the tungsten alloy tube exhibit a certain magnetic response.

- **Magnetic performance**

1. **Mixture of paramagnetism and ferromagnetism** : The ratio of ferromagnetic components in tungsten alloy tubes determines the strength of their magnetic properties.
2. **Magnetic permeability** : As the iron and nickel content increases, the magnetic permeability increases, which is beneficial to magnetic field shielding.
3. **Hysteresis and coercive force** : The hysteresis loop characteristics of the alloy tube affect its energy loss and performance in an alternating magnetic field.

- **Application Fields**

The magnetic response characteristics of tungsten alloy tubes give them potential advantages as neutron absorption materials in electromagnetic shielding, magnetic field sensors and nuclear industry.

## 3. Radiation resistance of tungsten alloy tube

- **Stability in Radiation Environments Tungsten alloy tubes**

have excellent radiation shielding capabilities due to the high atomic numbers of tungsten and molybdenum elements, and can effectively block gamma rays, neutrons and other high-energy particles.

- **Radiation-induced changes in materials**

1. **Irradiation damage** : High-energy radiation can cause lattice defects, increased dislocations, and microstructural changes, affecting mechanical properties.
2. **Radiation-induced hardening and embrittlement** : Under long-term radiation, the hardness of the material increases but the ductility decreases, which may lead to the risk of brittle fracture.
3. **Alloy stability** : Through reasonable design, alloy systems such as tungsten, molybdenum, nickel and iron can effectively inhibit phase changes and performance degradation caused by radiation.

- **Engineering Applications**

Tungsten alloy tubes are widely used in nuclear reactor shielding materials, radioisotope transport pipelines and radiotherapy equipment structural parts to ensure the safety of equipment and personnel.

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#### 4. Performance Optimization and Future Research Directions

- **Improved electrical performance is achieved**  
through purity improvement and microstructure control to reduce impurities and pores, lower resistivity and improve stability.
- **Magnetic response control**  
precisely adjusts the iron and nickel content to optimize magnetic properties to meet different shielding and sensing requirements.
- **Radiation tolerance is enhanced**  
by using microalloying, nano-strengthening and surface coating technologies to improve resistance to radiation damage and extend service life.

#### V. Summary

Tungsten alloy tubes exhibit unique advantages in electrical properties, magnetic response, and radiation resistance, making them an irreplaceable key material in the high-end nuclear energy, aerospace, and electronics industries. Through continuous material design and process optimization, the performance of tungsten alloy tubes will be further enhanced to meet the diverse needs of future extreme working conditions.

#### 2.6 Analysis of Corrosion Resistance and Chemical Stability of Tungsten Alloy Tube

Tungsten alloy tubes are widely used in the nuclear industry, aerospace, electronic devices and other fields due to their excellent comprehensive properties. However, in actual use, tungsten alloy tubes are often exposed to various corrosive media and complex chemical environments. Therefore, in-depth research on their corrosion resistance and chemical stability is of great significance.

##### 1. Overview of Corrosion Resistance of Tungsten Alloy Tube

Tungsten itself is an extremely stable transition metal with high chemical inertness and corrosion resistance. The tungsten content in tungsten alloy tubes is usually high, which makes them exhibit excellent corrosion resistance in various corrosive environments. The corrosion resistance of tungsten alloy tubes mainly comes from the following aspects:

- **The corrosion resistance of tungsten**  
Tungsten has a high melting point (3422°C) and extremely strong chemical stability. It can remain stable in a variety of acid and alkaline environments, especially in neutral and weak acid and alkaline environments, showing excellent corrosion resistance.
- **Influence of alloy composition**  
Although the bonding phases such as nickel, iron and copper in tungsten alloy tubes help improve mechanical properties and processing performance, their corrosion resistance is weaker than that of tungsten. Therefore, the alloy composition ratio and element distribution have a significant impact on the overall corrosion resistance.
- **The dense microstructure is**  
achieved through high-density sintering and optimized heat treatment, which reduces pores

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and cracks, effectively preventing the penetration of corrosive media and improving the corrosion resistance life of tungsten alloy tubes.

## 2. Performance of tungsten alloy tubes in different corrosive media

### 1. Corrosion Performance in Acidic Environments:

Tungsten alloy tubes have good corrosion resistance to most mineral acids (such as sulfuric acid and hydrochloric acid). However, in high-temperature concentrated acid environments, a protective film such as tungsten oxide may form on the tungsten surface, providing a certain degree of passivation protection. Binder phases such as nickel and iron have poor corrosion resistance and are prone to localized corrosion, affecting overall performance.

### 2. Tungsten alloy tubes also perform well in alkaline environments . The chemical stability of tungsten ensures that it is not easily corroded by alkaline solutions.

However, the iron and nickel components in the alloy may cause varying degrees of corrosion, which needs to be improved through alloy design and surface treatment.

### 3. Salt spray and marine environments

pose a challenge to the corrosion resistance of tungsten alloy tubes, especially those containing chloride ions. Tungsten alloy surfaces are susceptible to microscopic pitting, and long-term exposure to marine climates can lead to a decrease in corrosion resistance. Proper surface coating and protective measures are key to ensuring the service life of tungsten alloy tubes in such environments.

### 4. high

temperatures to form a dense  $WO_3$  oxide film. This film protects against further oxidation. However, at extremely high temperatures and in a highly oxidizing environment, the film may become unstable, leading to accelerated oxidation. Therefore, high-temperature oxidation resistance must be enhanced through alloying elements and surface protection.

## 3. Factors Affecting the Chemical Stability of Tungsten Alloy Tubes

- **The distribution of alloying elements and**

the uniform distribution of bonding phases such as nickel and iron at the interface and their good bonding with the tungsten matrix can effectively prevent the corrosive medium from penetrating along the interface.

- **Microstructure and Porosity High- density, low-porosity tungsten alloy**

tubes significantly improve corrosion resistance. Pores and microcracks are the main channels for the invasion of corrosive media.

- **Surface Condition and Coating Technology**

The surface of tungsten alloy tubes treated with grinding, polishing and coating becomes denser and smoother, significantly improving corrosion resistance.

- **as the chemical properties of the environmental medium,**

temperature, pH value, redox potential, etc. directly affect the corrosion rate and corrosion form of tungsten alloy tubes.

## 4. Strategies for Improving the Corrosion Resistance of Tungsten Alloy Tubes

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1. **Optimize the alloy composition design and introduce trace corrosion-resistant elements (such as molybdenum , vanadium, chromium, etc.)** through micro-alloying to improve the overall chemical stability and corrosion resistance of the tungsten alloy tube.
2. **The improved preparation process** adopts advanced powder metallurgy technology, hot isostatic pressing technology, etc. to obtain dense and uniform alloy structure and reduce porosity and defects.
3. **Surface treatment and coating technology** uses ceramic coating, metal oxide coating, PVD/CVD and other physical vapor deposition technologies to improve surface hardness and corrosion resistance.
4. **Maintenance and use environment control** Control the humidity, temperature and corrosive medium concentration of the use environment, and combine regular maintenance to extend the service life of tungsten alloy tubes.

## V. Summary

Tungsten alloy tubes offer excellent corrosion resistance and chemical stability, particularly in neutral and mildly corrosive environments . Through rational alloy design, advanced fabrication processes, and surface treatment technologies, the stability of tungsten alloy tubes in harsh corrosive environments has been significantly enhanced. In the future, with the continuous development of new materials and processes, the corrosion resistance of tungsten alloy tubes will further meet the stringent requirements of high-end applications.

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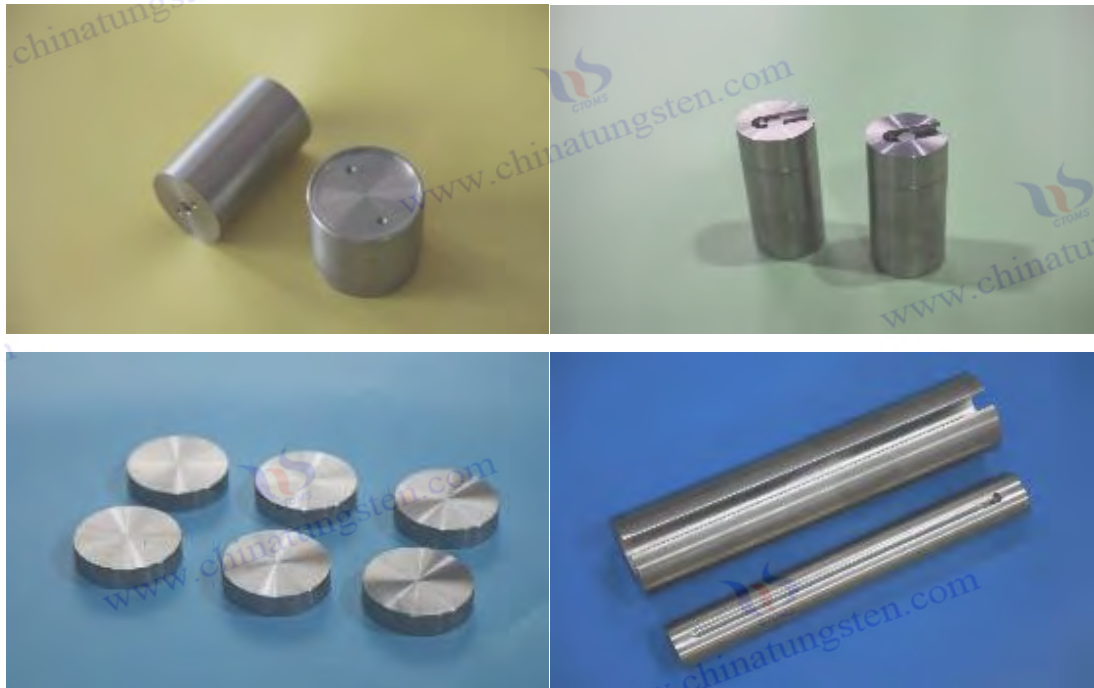
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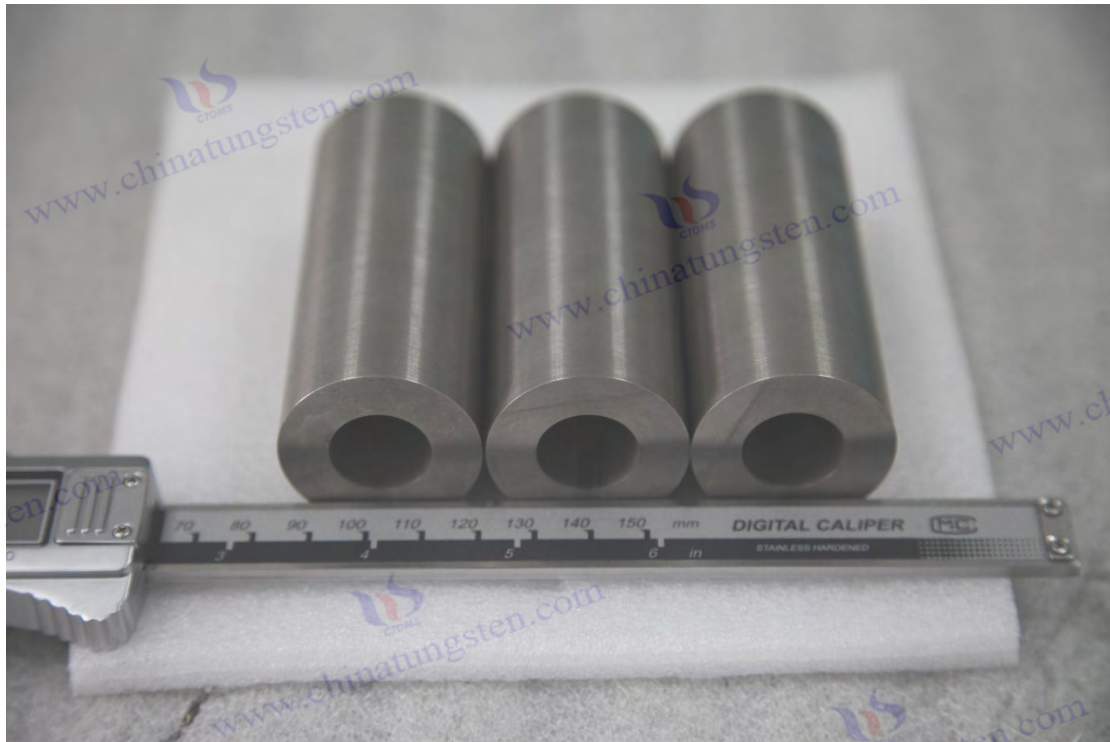
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## Chapter 3 Preparation and Forming Technology of Tungsten Alloy Tube

### 3.1 Raw material preparation and powder characteristics analysis of tungsten alloy tube

tungsten alloy tubes depends not only on the alloy's composition but also on the selection of raw materials and the properties of the powder. The quality of the raw materials and the properties of the powder directly impact the stability of the subsequent manufacturing process, as well as the density, mechanical properties, and microstructure of the final product. Therefore, raw material preparation and powder property analysis are crucial starting points in the manufacturing process.

#### 1. Selection of raw materials for tungsten alloy tubes

tungsten alloy tubes include high-purity tungsten powder and binder metal powder (such as nickel powder, iron powder, copper powder, etc.). Tungsten powder, as the matrix element, determines the density and basic physical properties of the alloy; while the binder metal affects the alloy's machinability, toughness, and overall mechanical properties.

- **Tungsten powder quality requirements:**

Tungsten powder should be high-purity (typically tungsten content  $\geq 99.95\%$ ), low in oxygen and impurities to avoid product performance defects caused by impurities. The powder should have a uniform and moderately distributed particle size (generally 1-10 microns), and be spherical or sub-spherical in shape, which promotes good powder flowability and compaction density.

- **powders**

, as the primary binder metals, must have an appropriate particle size distribution and good

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purity. They are typically smaller than tungsten powder to ensure uniform distribution and form a good bonding phase during sintering. Copper powder is sometimes added to improve thermal conductivity and mechanical properties.

## 2. Analysis of physical properties of tungsten alloy tube powder

The physical properties of powder are key factors affecting the forming process, mainly including particle size distribution, specific surface area, fluidity, bulk density and particle morphology.

- **Particle size distribution and morphology**  
directly impact the uniformity and density of compacting. Fine powders facilitate sintering densification, but excessively fine powders tend to agglomerate and have poor flowability, making compacting more difficult. Spherical or near-spherical powders, due to their excellent flow properties, facilitate uniform filling during compacting.
- **surface**  
area increases the contact area between powders, which is beneficial to sintering diffusion and bonding, but it also easily leads to powder moisture absorption, agglomeration and oxidation, and the storage environment of the powder needs to be strictly controlled.
- **fluidity**  
ensures uniform filling of the mold and molding efficiency. Insufficient fluidity will lead to uneven powder accumulation and unstable dimensions of the molded product.
- **density**  
and tap density of the initial powder affect the density of the green body after pressing, and thus affect the final density and performance of the tube after sintering.

## 3. Chemical composition of powder and impurity control

tungsten alloy tubes is extremely sensitive to impurities in the powder. In particular, non-metallic impurities such as oxygen, carbon, and nitrogen can significantly affect the sintering behavior and mechanical properties of the alloy. Strict chemical composition testing and impurity control of the powder are essential to ensure the performance of tungsten alloy tubes.

- **Oxygen content control:**  
Oxygen will promote the oxidation of tungsten powder to form tungstate, affecting the sintering densification process. The key to reducing oxygen content is to adopt atmosphere protection, low oxygen preparation process and powder storage environment control.
- **The influence of impurity elements** The impurity elements in iron and nickel powders need to be strictly limited to avoid the introduction of harmful elements such as sulfur and phosphorus to prevent the degradation of alloy properties and damage to corrosion resistance.

## 4. Powder pretreatment technology

In order to improve the fluidity and sintering properties of the powder, the following pretreatment technologies are often used in the preparation of tungsten alloy tubes:

- **Ball milling**  
refines the powder particle size through mechanical ball milling, improves the particle size

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distribution, makes the powder particle size more uniform, and improves the pressing and forming performance.

- **Screening**

is used to grade and screen the powder to remove large particles and agglomerates to ensure the stability of the powder particle size.

- **Gas atomization**

uses gas atomization technology to produce spherical tungsten powder, which has the advantages of uniform particle size, good fluidity and high density.

## V. Summary

tungsten alloy tubes directly impact the quality and performance of the tubes. By properly mixing high-purity, highly uniform tungsten powder with the binder metal powder, and strictly controlling parameters such as powder particle size, fluidity, and impurity content, the stability of the tungsten alloy tube forming process and the excellent performance of the final product can be guaranteed. With the development of advanced powder preparation and processing technologies, the quality of raw materials for tungsten alloy tubes continues to improve, laying a solid foundation for the industrial production of high-performance tungsten alloy tubes.

### 3.2 Powder Metallurgy Pressing Technology of Tungsten Alloy Tube (Molding, Isostatic Pressing)

Tungsten alloy tubes are high-density, high-strength functional materials, and powder metallurgy pressing is a key step in their production. Through the rational pressing of powders, complex shapes, high dimensional accuracy, and uniform density can be achieved, laying the foundation for subsequent sintering and heat treatment. Commonly used powder pressing techniques include die pressing and isostatic pressing, each with its own advantages and scope of application, and are widely used in the industrial production of tungsten alloy tubes.

#### 1. Compression molding technology

Compression molding is a process that uses a specialized mold to apply unidirectional pressure to tungsten alloy powder, compacting the powder into a compacted shape within the mold cavity. Compression molding is a simple process with high production efficiency, making it suitable for mass production of standard-sized tungsten alloy tubes.

- **Process**

1. **Powder filling** : The pre-mixed tungsten alloy powder is loaded into a dedicated cylindrical or tubular mold.
2. **Compression molding** : Use a hydraulic press or mechanical press to apply high pressure (generally in the range of tens to hundreds of MPa) to compact the powder in the mold to form a dense green body.
3. **Demolding and blank removal** : After the pressure is released, the formed blank is taken out and prepared for the subsequent sintering process.

- **Advantages**

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- The equipment is simple, the process is mature, and it is easy to realize automated production.
- The production cycle is short and suitable for mass production.
- the formed green body is higher and the size control is better.

- **challenge**

- Unidirectional pressure may lead to uneven powder density distribution and cause density gradient in the green body.
- For tungsten alloy tubes with thin walls or complex cross-sections, it is difficult to ensure uniformity during die forming.
- The mold wears out quickly and the maintenance cost is high.

## 2. Cold Isostatic Pressing (CIP)

Isostatic pressing involves placing tungsten alloy powder in a flexible mold (rubber capsule) and applying uniform pressure in all directions through a high-pressure fluid (liquid or gas). This process effectively improves the density and uniformity of the blank and is suitable for forming tungsten alloy tubes with complex shapes and thin walls.

- **Process**

1. **Loading and packaging** : Load the tungsten alloy powder into the rubber mold, seal it and ensure that no air is trapped.
2. **Isostatic pressing** : The mold bag is placed in an autoclave, and compressed liquid (such as oil or water) is injected to apply isostatic pressure, which usually ranges from 100-300 MPa.
3. **Demolding** : After the pressure is released, the soft mold is taken out and the rubber coating is removed to obtain a uniform and dense green body.

- **Advantages**

- The applied pressure is uniform, the green body has good density and uniform structure.
- It has strong adaptability and can form complex cross-sections and thin-walled pipes.
- It can effectively reduce forming defects such as density gradients and cracks.

- **challenge**

- The equipment investment is high, the process flow is complex, and the production cycle is long.
- Subsequent machining is required to achieve precise dimensional requirements.
- The mold bag material and sealing technology must be guaranteed to avoid leakage affecting quality.

## 3. Comprehensive application of molding and isostatic pressing

modern tungsten alloy tube production, the advantages of both die pressing and isostatic pressing are often combined to achieve better product performance. For example, die pressing is first used to quickly form the basic shape of the blank, followed by isostatic pressing to optimize density and uniformity, and finally mechanical processing and heat treatment.

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#### 4. Key factors affecting powder pressing quality

- **Powder particle size and distribution** : Uniform and moderate particle size helps powder flow and filling, and improves pressing density.
- **Powder ratio and wettability** : The reasonable mixing and wettability of alloy powder affect the bonding and compaction effect between particles.
- **Pressure and speed** : If the pressure is too low, the density is insufficient; if the pressure is too high, cracks are likely to occur; the pressing speed affects the flow and compaction uniformity of the powder.
- **Mold design** : Mold shape, size and lubrication design are directly related to the ease of demoulding and forming dimensional accuracy.

#### V. Conclusion

tungsten alloy tubes is fundamental to their high performance. The die pressing process, renowned for its high production efficiency and simple equipment, is suitable for the production of standard thick-walled tubes. Isostatic pressing, renowned for its dense and uniform quality and adaptability to complex structures, is ideal for high-end thin-walled or specialized shapes. The combined application of these two methods can meet the diverse demands of tungsten alloy tubes for various applications. In the future, with advances in powder materials and equipment technology, powder pressing will become even more precise and efficient, providing strong support for the performance improvement and industrial development of tungsten alloy tubes.

### 3.3 Hollow Forming Process and Die Design Key Points for Tungsten Alloy Tube

tungsten alloy tubes are widely used in aerospace, nuclear industry, electronic equipment, and other fields. Due to their unique material properties and complex manufacturing processes, hollow forming technology and mold design are key technical links in tungsten alloy tube manufacturing. Effective forming processes and reasonable mold design not only ensure the structural integrity and dimensional accuracy of tungsten alloy tubes, but also enhance the mechanical properties and service life of the finished product.

#### 1. Overview of hollow forming process

tungsten alloy tubes typically involves die pressing, isostatic pressing, and subsequent machining and heat treatment. Compared to solid tungsten alloy products, the hollow structure increases the difficulty of forming, mainly in terms of uniform powder filling, wall thickness control, and internal cavity protection during forming.

- **Powder filling:**  
Uniform powder filling is the prerequisite for ensuring uniform wall thickness of hollow tubes without pores and defects. Specialized vibration devices or rotating molds are often used in conjunction with filling technology to ensure that the tungsten alloy powder is fully distributed on the inner wall of the mold to form a uniform powder layer.

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- **Compression molding**  
utilizes a dual-die compression technique, whereby external pressure is applied to compact the powder to form a hollow tungsten alloy tube. The internal die maintains the shape and size of the tube cavity, preventing collapse or deformation of the tube.
- **Isostatic pressing**  
densifies the hollow tube by applying uniform pressure after powder encapsulation. This method provides excellent control of tube wall thickness uniformity and effectively reduces density gradients and structural defects.
- **Machining and heat treatment**  
After forming, the tube billet usually needs to be precision machined to achieve the designed size and surface quality, and the microstructure is optimized through heat treatment process to improve the mechanical properties.

## 2. Key points of mold design

hollow tungsten alloy tubes must take into account the material properties, forming process, and product structure characteristics. Key design elements include:

1. Due to the high hardness and sintering temperature of tungsten alloy powder, the **mold** must have high wear resistance and thermal stability. Common materials include cemented carbide, high-speed steel, and heat-resistant alloys. The mold surface also requires special treatment, such as coating or surface hardening, to extend its life.
2. **between**  
the inner and outer diameters of the mold directly affects the uniformity of the tube wall thickness and dimensional accuracy. High-precision machining and assembly techniques are usually used to ensure that the inner and outer molds are coaxial and have no gaps or misalignments.
3. **Mold venting and powder filling channel design**  
: Properly designed vent holes and powder filling channels ensure that there is no gas stagnation in the mold, avoiding the formation of pores and inclusion defects. The venting channel should be coordinated with the mold structure to facilitate later disassembly and cleaning.
4. **Cooling and heating systems are integrated**  
into the forming or sintering process. The mold must have uniform temperature control to avoid local thermal stress that causes deformation or cracks. Built-in cooling channels or heating elements are designed to achieve precise temperature regulation.
5. Due to the close contact between the tungsten alloy **tube** and the mold, an efficient demoulding system must be designed, such as a push rod, a slider or a pneumatic device, to ensure that the tube is completely and smoothly ejected to prevent damage.
6. **Mold life and maintenance convenience:**  
Due to the harsh working conditions of tungsten alloy tube molds, the design should consider the replacement of wearing parts and the rapid maintenance of the mold to reduce downtime and production costs.

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### 3. Process control during forming

- **Pressure uniformity**  
ensures uniform pressure distribution during molding or isostatic pressing, avoiding uneven wall thickness and cracks.
- **Powder filling density control**  
accurately controls the filling amount to prevent insufficient powder from causing weak wall thickness, or excessive powder from causing deformation.
- The temperature gradient during **temperature control forming and sintering will affect the structure and performance of the pipe and needs to be strictly monitored and adjusted.**
- **Demolding aging control**  
prevents deformation of the blank caused by premature demolding. The demolding time should be optimized in combination with the cooling and hardening characteristics of the material.

### 4. Future Technology Development Trends

With the advancement of manufacturing technology, the design and forming process of hollow tungsten alloy tube molds are also constantly innovating, including:

- **Digital design and simulation**  
utilize finite element analysis (FEA) to simulate the forming process, optimize mold structure and process parameters, and improve product quality.
- **Intelligent mold and sensor integration**  
: The mold's embedded sensors monitor pressure, temperature and displacement in real time to achieve intelligent feedback control.
- **Additive manufacturing molds**  
use 3D printing technology to create molds with complex cooling channels and optimized structures to improve heat dissipation efficiency and forming uniformity.
- **Advanced powder filling technology**  
uses automated filling equipment and rheologically assisted technology to improve powder distribution uniformity and density.

### V. Summary

tungsten alloy tubes are key to ensuring their high performance and stability. Through appropriate powder filling, mold structure optimization, and process parameter control, the tube's density, mechanical properties, and dimensional accuracy can be effectively improved. With the introduction of digital and intelligent manufacturing technologies, the hollow forming process for tungsten alloy tubes will become more refined and automated to meet increasingly complex application requirements.

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### 3.4 Sintering Technology and Atmosphere Control Optimization of Tungsten Alloy Tube

tungsten alloy tubes is one of the most critical steps in the manufacturing process, directly affecting the product's density, mechanical properties, and microstructure. Due to the high melting point and unique physical and chemical properties of tungsten alloy, the sintering process requires precise control of temperature, atmosphere, and time to achieve high densification, uniform structure, and excellent performance. A suitable atmosphere prevents oxidation, decarburization, and other harmful reactions, thereby improving the quality and service life of the finished product.

#### 1. Overview of Tungsten Alloy Tube Sintering Technology

Sintering is a process of combining and densifying material particles through diffusion between powder particles at high temperatures. For tungsten alloy tubes, sintering must meet the following requirements:

- **High density** : reduce porosity, improve mechanical strength and corrosion resistance;
- **Uniform structure** : avoid segregation and coarse grains to ensure consistency of mechanical properties;
- **Dimensional stability** : control sintering shrinkage to ensure the dimensional accuracy of the pipe;
- **Surface quality** : prevents surface defects and oxide layer formation.

tungsten alloy tubes mainly include traditional high-temperature vacuum sintering, hydrogen reduction sintering and hot isostatic pressing (HIP) sintering.

#### 2. Sintering temperature and time control

- **temperature**  
range of 1400°C to 1600°C. Too low a temperature will lead to insufficient density, affecting strength and hardness; too high a temperature may cause grain growth and reduce toughness.
- **holding**  
time can promote grain boundary diffusion and pore closure, and is generally maintained for several hours. Insufficient holding time will result in insufficient density, while too long a holding time will increase energy consumption and may cause overheating.
- **the heating rate**  
can prevent excessive thermal stress in the material, which can lead to cracks. Slow heating is usually used, especially during the transition from lower to higher temperatures, to prevent rapid pore shrinkage.

#### 3. Atmosphere environment and atmosphere control

The selection of sintering atmosphere for tungsten alloy tubes is extremely important to prevent oxidation of the material and maintain chemical stability. Common atmospheres include:

- **vacuum**  
( $10^{-3}$  to  $10^{-5}$  Pa ) environment can effectively prevent oxidation and impurity contamination, keeping the alloy pure. However, this requires high equipment and is costly.

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- **A reducing atmosphere**  
typically contains hydrogen (such as  $H_2$  or a  $H_2 + Ar$  mixture ), which reduces surface oxides during sintering, promoting densification while avoiding decarburization. The purity and flow of the atmosphere must be strictly controlled to prevent the risk of hydrogen explosion.
- **Protective atmosphere**  
Argon or nitrogen protective atmosphere is also used in some processes to reduce surface oxidation and is suitable for processes that have less stringent atmosphere requirements than vacuum.
- In some processes, **atmosphere conversion technology first uses vacuum or reducing atmosphere for sintering, and then switches**  
to protective atmosphere for cooling to prevent thermal oxidation.

#### 4. Application of Hot Isostatic Pressing (HIP) Technology

Hot isostatic pressing (HIP) is an advanced method for densification of tungsten alloy tubes. It significantly improves the sintered density and mechanical properties by simultaneously applying heat energy and isostatic pressure in a high-temperature and high-pressure gas environment.

- **Pressure range**  
The commonly used pressure in HIP process is 50-200 MPa, which effectively eliminates residual porosity.
- **The temperature control**  
temperature is similar to conventional sintering, but due to the pressure addition, the material densification speed is faster and the grain control is better.
- **Application Effect**  
HIP sintering can obtain highly uniform fine grain structure, greatly improving the tensile strength, toughness and corrosion resistance of tungsten alloy tubes, which is particularly suitable for high-end aerospace and nuclear industry applications.

#### 5. Defect control during sintering process

tungsten alloy tubes include porosity, cracks, grain coarsening and segregation. Targeted optimization measures include:

- **Powder pretreatment**  
uses spherical high-purity powder to reduce inclusions and improve initial density.
- **Optimize the pressure distribution and**  
design the mold reasonably to ensure uniform pressure during sintering and avoid local lack of density.
- **The atmosphere purity is improved**  
by using high-purity gas and purification equipment to prevent oxidation and impurity intrusion.
- **The multi-step sintering process**  
gradually eliminates pores and optimizes the grain structure through multi-stage temperature gradient control.

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## 6. Future Development Trends of Sintering Technology

- **Intelligent sintering control**  
uses sensors and online monitoring technology to achieve real-time regulation of the sintering process and improve the yield rate.
- **Low-temperature and high-efficiency sintering technology**  
studies new sintering aids and activators to reduce sintering temperature and energy consumption.
- **sintering and additive manufacturing Combined**  
with additive manufacturing technology, the integrated forming and sintering of complex tungsten alloy tubes can be achieved.
- **Environmentally friendly atmosphere system**  
develops green and environmentally friendly atmosphere to replace traditional hydrogen and reduce safety risks.

## VII. Summary

Sintering technology and atmosphere control are key factors in determining material performance and quality in tungsten alloy tube manufacturing. By optimizing sintering temperature, time, and atmosphere conditions, combined with advanced hot isostatic pressing (HIP) processes and intelligent control methods, the density, mechanical properties, and service life of tungsten alloy tubes can be significantly improved, meeting the stringent requirements of high-end applications. In the future, with further process innovation and in-depth material research, tungsten alloy tube sintering technology will achieve even more efficient, environmentally friendly, and intelligent development.

## 3.5 Heat Treatment Process and Densification Improvement Technology of Tungsten Alloy Tube

tungsten alloy tubes typically undergo a scientifically designed heat treatment process to optimize their microstructure, enhance the material's densification level, and improve its overall mechanical properties. Heat treatment not only eliminates internal stresses and improves grain morphology, but also enhances the tube's strength, toughness, and corrosion resistance. It is a key process for improving the overall quality of tungsten alloy tubes.

### 1. The main purpose of heat treatment of tungsten alloy tube

1. **pressing**  
, sintering, and machining processes, residual stresses are generated inside the tungsten alloy tube. Appropriate heat treatment can effectively release these stresses, reduce the risk of material deformation and cracking, and ensure the dimensional stability of the tube.
2. **promotes grain refinement and homogenization**  
by controlling the heating temperature and cooling rate, adjusting the grain size and

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morphology, inhibiting grain growth, achieving uniform structure, and thus improving mechanical strength and toughness.

**3. Improve density and reduce porosity**

Through appropriate heat treatment processes, the closure and elimination of residual pores are promoted, the density of the material is increased, thereby enhancing the tensile strength, hardness and fatigue life.

**4. Improving chemical stability and corrosion resistance**

Heat treatment can promote the uniform diffusion and solid solution of alloying elements, improve the chemical stability of the alloy, and enhance its resistance to oxidation and corrosion environments.

**2. Common Heat Treatment Process Types of Tungsten Alloy Tubes**

**1. Annealing treatment**

- Temperature range: usually between 800°C and 1200°C, the specific temperature is selected according to the alloy composition and structural characteristics.
- Mechanism of action: Annealing can relieve internal stress, promote recrystallization, refine grains and reduce structural defects.
- Typical process flow: slowly heat up to the target temperature, keep warm for several hours and then slowly cool down to prevent thermal stress.

**2. Solution treatment**

- It is mainly used to optimize the distribution of alloy elements and eliminate composition segregation.
- Generally, a high temperature (above 1200°C) is used for short-term insulation and rapid cooling to fix the solid solution structure.
- It has a significant effect on improving strength and thermal stability.

**3. Aging treatment**

- By keeping the heat at an appropriate temperature, the supersaturated solid solution precipitates a second phase, strengthening the material.
- Commonly found in tungsten alloy tubes containing nickel, iron and other elements, the aging temperature is generally 400°C-700°C.

**4. Hot isostatic pressing (HIP)**

- Combining high temperature and isostatic pressure promotes pore closure and microstructure optimization.
- Greatly improves density and mechanical properties, and is often used in the preparation of high-end tungsten alloy tubes.

**3. Influence of heat treatment process parameters on densification**

**• heat treatment**

temperature directly affects the grain size and pore closure efficiency of the tungsten alloy tube. If the temperature is too low, the diffusion rate will be insufficient and the densification will be inadequate; if the temperature is too high, the grain size will grow and the toughness of the material will be reduced.

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- **the holding time**  
is beneficial to fully completing the microstructure transformation and diffusion process, but too long a holding time will waste energy and may cause undesirable grain coarsening.
- **Cooling method:**  
Slow cooling helps to form a uniform structure and reduce thermal stress; rapid cooling (such as water cooling) is suitable for solution treatment to lock the strengthening phase.
- **Atmospheric**  
heat treatment is usually carried out in a vacuum or protective atmosphere to prevent material oxidation and surface decarburization.

#### 4. Advanced Densification Enhancement Technology

1. **The multi-step heat treatment process**  
effectively promotes microstructure homogenization and porosity elimination by designing multi-stage heating, insulation and cooling processes, significantly improving the overall performance of the material.
2. **Hot isostatic pressing combined with aging treatment**  
first increases density through HIP, and then performs aging strengthening to achieve a balance between strength and toughness.
3. **Laser or electron beam heat treatment**  
uses local high energy density heating to achieve surface densification and property gradients, improving wear and corrosion resistance.
4. **Microwave-assisted heat treatment**  
uses microwave radiation heating, which has high thermal efficiency and uniform heating, helping to shorten processing time and refine the structure.

#### V. Summary

tungsten alloy tubes is a critical step in ensuring their high performance. Through a rational heat treatment process and optimized process parameters, not only can the density and microstructure uniformity of tungsten alloy tubes be effectively improved, but their mechanical strength, toughness, and corrosion resistance can also be significantly enhanced. In the future, with the continuous development and application of advanced heat treatment technologies, the performance of tungsten alloy tubes will be further enhanced to meet the more stringent industrial and high-end needs.

#### 3.6 Internal and external surface treatment of tungsten alloy tubes (polishing, electroplating, PVD, etc.)

tungsten alloy tubes are widely used in aerospace, nuclear industry, medical equipment, and high-end manufacturing. The quality of their internal and external surfaces directly impacts the performance, durability, and functionality of the tubes. Therefore, a scientific and rational surface treatment process is crucial for enhancing the overall performance of tungsten alloy tubes. This section details the main internal and external surface treatment technologies for tungsten alloy tubes ,

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including polishing, electroplating, and physical vapor deposition (PVD), focusing on their process principles, technical characteristics, and application results.

## 1. Importance of Surface Treatment of Tungsten Alloy Tube

### 1. Improved surface finish

A good surface finish helps reduce friction and wear, improve fluid dynamics and sealing, which is particularly critical for internal wall applications.

### 2. Enhanced corrosion resistance and wear resistance Through surface modification technology,

the resistance of tungsten alloy tubes to chemical corrosion and mechanical wear can be significantly improved, thus extending their service life.

### 3. Improving the adhesion of functional coatings

Pretreatment provides a uniform and clean surface for subsequent coating processes, ensuring that the coating is firmly bonded and performs its intended function.

### 4. Meet specific industrial needs

such as medical equipment requires non-toxicity and harmlessness, aerospace requires high strength and heat resistance, and the electronics industry requires high conductivity and anti-electromagnetic interference.

## 2. Tungsten Alloy Tube Polishing Process

### 1. Polishing process and methods

- **Mechanical polishing**

uses sandpaper, polishing cloth and polishing paste to perform coarse, medium and fine polishing in sequence to remove the surface oxide layer and machining marks to achieve a mirror effect.

- **Electrolytic polishing**

removes surface microscopic protrusions through electrochemical reactions, achieving micron-level or even nanometer-level smoothness, and is suitable for polishing complex inner holes.

- **Chemical polishing**

uses chemical liquids to evenly dissolve surface uneven areas, improve roughness, and reduce mechanical stress.

### 2. Polishing effect and application

- Mechanical polishing of external surfaces is widely used for decorative and mechanical matching surfaces;
- Internal surface polishing mainly relies on electrolytic polishing and chemical polishing to ensure fluid delivery and sealing performance;
- After polishing, the surface roughness can reach below  $Ra0.1\ \mu m$ , meeting the requirements of high-end medical and precision instruments.

## 3. Tungsten Alloy Tube Electroplating Process

### 1. Electroplating type

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- **Nickel**  
plating Nickel coating can effectively improve wear resistance, corrosion resistance and surface hardness, and is a commonly used protective coating for tungsten alloy tubes.
- **Chrome**  
plating has excellent hardness and wear resistance and is often used in high wear environments.
- **Copper plating and other metal plating**  
are mainly used to improve conductivity and provide a good adhesion foundation for subsequent coatings.

## 2. Electroplating process

- Surface pretreatment (degreasing, pickling, activation);
- Immerse in the electroplating tank and apply a constant current to perform metal ion reduction deposition;
- Cleaning, drying and post-processing ensure the quality of the coating.

## 3. Advantages of electroplating technology

- High efficiency, relatively low cost, suitable for mass production;
- The coating is uniform and the thickness is controllable to meet different usage requirements;
- Composite protection function is achieved through multi-layer composite coating.

## 4. Tungsten Alloy Tube Physical Vapor Deposition (PVD) Process

### 1. Introduction to PVD Technology

Physical vapor deposition is a technology that uses physical processes (evaporation, sputtering) to deposit materials in the form of vapor on the surface of a substrate to form a thin film. It is widely used in the preparation of hard coatings, decorative coatings and functional coatings.

### 2. Common PVD coating types

- Hard coatings such as titanium nitride ( TiN ), chromium nitride ( CrN ), and titanium carbide ( TiC ) significantly improve wear resistance;
- Multi-layer composite film improves coating toughness and corrosion resistance;
- Conductive coating to improve surface electrical properties.

### 3. PVD process characteristics

- The film has strong adhesion, uniform and adjustable thickness;
- Environmentally friendly and pollution-free, no chemical waste liquid treatment involved;
- Suitable for coating complex inner holes and outer surfaces.

### 4. Application Advantages

- Significantly improve the wear resistance, corrosion resistance and service life of tungsten alloy tubes;
- Realize functional surfaces to meet special industrial needs;
- Suitable for high-end aerospace, medical and precision manufacturing fields.

## 5. Other surface treatment technologies of tungsten alloy tubes

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- **Shot peening**  
uses high-speed spraying of small particles to impact the surface, forming a compressive stress layer, thereby improving fatigue strength and wear resistance.
- **Laser surface treatment**  
achieves local surface densification and hardening through laser heating and cladding .
- **Chemical vapor deposition (CVD)**  
is used to prepare high-purity, high-density coatings for use in high-temperature and corrosive environments.

## 6. Comprehensive requirements for internal and external surface treatment of tungsten alloy tubes

- The inner wall must be smooth and free of impurities to prevent fluid resistance and corrosion;
- The outer wall treatment focuses on wear resistance, corrosion resistance and appearance quality;
- When selecting a suitable surface treatment process, it is necessary to comprehensively consider the pipe diameter, application environment and cost-effectiveness;
- Combining multiple processes (such as polishing + electroplating + PVD) to maximize performance.

## VII. Summary

Tungsten alloy tube surface treatment technologies encompass a wide range of methods, from traditional mechanical polishing to advanced PVD coatings, each with its own unique advantages and mutually reinforcing benefits. Reasonable process design and precise operational control can not only significantly improve the surface quality and performance of tungsten alloy tubes, but also meet the diverse needs of various industrial sectors. With technological advancements, surface treatment processes will become more environmentally friendly, efficient, and intelligent, providing a solid foundation for the high-end applications of tungsten alloy tubes.

### 3.7 New Tungsten Alloy Tube Manufacturing Technologies: Extrusion, Rolling , and Additive Manufacturing

As the demands for material performance and manufacturing efficiency in tungsten alloy tube applications continue to rise, traditional powder metallurgy, while mature and reliable, faces limitations in complex shapes, high-performance customization, and rapid production. In recent years, new manufacturing technologies such as extrusion, rolling , and additive manufacturing have been gradually introduced into the tungsten alloy tube manufacturing process, becoming a key driver of technological innovation and product upgrades in the industry. This section will explore in detail the principles, process characteristics, advantages, and application prospects of these three emerging manufacturing technologies in tungsten alloy tube production.

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## 1. Tungsten Alloy Tube Extrusion Technology

### 1. Overview of Extrusion Technology

Extrusion is a plastic working method that uses high pressure to force heated tungsten alloy billets through a die orifice to form a continuous cross-section tube. This process is widely used in metal tube manufacturing and is suitable for improving the microstructure density and mechanical properties of tungsten alloy tubes.

### 2. Extrusion process

- **Blank preparation** : Heat the pre-sintered tungsten alloy block to a suitable plastic deformation temperature (usually above 1100°C);
- **Mould design** : Specially designed hollow mould is used to control the inner and outer diameters and wall thickness of the pipe;
- **Extrusion** : Using a hydraulic or mechanical extruder to apply pressure to force the material through a die hole to form a tube;
- **Subsequent processing** : The extruded tube usually needs to be heat treated and machined to achieve dimensional accuracy and surface quality requirements.

### 3. Extrusion technology advantages

- Significantly improve the density and grain uniformity of the material;
- Refine the grains and improve the mechanical strength and plasticity of tungsten alloy tubes;
- tungsten alloy tubes with complex cross-sections and large diameters ;
- High production efficiency, suitable for medium and large batch production.

## 2. Tungsten Alloy Tube Rolling Technology

### 1. Overview of rolling technology

Rolling is a process that uses rollers to apply compressive stress, gradually compressing and deforming the tungsten alloy billet to form thin-walled tubes. Both hot and cold rolling methods can effectively adjust the thickness and mechanical properties of the tube.

### 2. Rolling process

- **Initial hot rolling** : heating the tungsten alloy tube billet to the plastic temperature, and then performing multiple hot rolling to reduce the tube wall thickness;
- **Cold rolling finishing** : cold rolling further improves surface quality and dimensional accuracy, and improves mechanical properties;
- **Annealing** : Annealing is performed when necessary to relieve stress and optimize the microstructure.

### 3. Rolling technology advantages

- Through multiple deformation steps, precise size control and uniform wall thickness are achieved;
- The grain structure can be controlled to improve toughness and fatigue resistance;
- Excellent surface quality, reducing the burden of subsequent machining;
- Suitable for producing thin-walled high-precision tungsten alloy tubes.

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### 3. Tungsten Alloy Tube Additive Manufacturing Technology

#### 1. Overview of Additive Manufacturing Technology

Additive Manufacturing (AM), also known as 3D printing, enables the fabrication of complex parts by depositing material layer by layer. Its application in the manufacture of tungsten alloy tubes is gradually expanding, and it is particularly suitable for customized and complex internal structures.

#### 2. Types of additive manufacturing methods

- **Selective laser melting (SLM)** : uses high-energy lasers to melt metal powder layer by layer to build highly dense parts;
- **Electron beam melting (EBM)** : uses an electron beam for high-energy deposition, suitable for high-melting-point materials such as tungsten alloys;
- **Direct Energy Deposition (DED)** : Powder or wire is ejected through a nozzle and melted and deposited immediately, suitable for repair and large-size part manufacturing.

#### 3. Advantages and Challenges of Additive Manufacturing

- **Advantages :**
  - It is possible to manufacture complex internal channels and special-shaped pipes;
  - Significantly shorten the R&D cycle and support small-batch personalized customization;
  - Reduce material waste and improve resource utilization.
- **challenge :**
  - tungsten alloy leads to extremely high requirements on equipment during the printing process;
  - It is difficult to control the porosity and defects inside the printed parts;
  - A complete post-processing process is required to ensure mechanical properties and dimensional stability.

#### 4. Comprehensive Application and Prospect of New Preparation Technologies

##### 1. technologies

are suitable for mass production, ensuring consistent mechanical properties and dimensions of tungsten alloy tubes. Additive manufacturing, on the other hand, is suitable for the customized development of complex structures and functionally graded tubes. The combination of these three technologies will create a more flexible and efficient production system.

##### 2. Room for performance improvement:

Advanced heat treatment and surface treatment technologies combined with new preparation processes can further enhance the high temperature resistance, wear resistance and service life of pipes.

##### 3. Prospects for industrial promotion:

With the advancement of equipment technology and the improvement of material technology, the extrusion, rolling and additive manufacturing technologies of tungsten

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alloy tubes will continue to mature, promoting the application expansion of tungsten alloy tubes in aerospace, nuclear industry, medical equipment and high-end manufacturing.

## V. Summary

New tungsten alloy tube fabrication technologies, represented by extrusion, rolling , and additive manufacturing , have broken through the bottlenecks of traditional manufacturing processes, achieving improvements in both product performance and structural complexity. In the future, through technological integration and process optimization, we will effectively meet the increasingly diverse and high-end market demands, helping the tungsten alloy tube industry enter a new stage of high-quality development.

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



## Chapter 4 Performance Testing and Quality Assessment of Tungsten Alloy Tubes

### 4.1 Appearance and Geometric Dimension Inspection Methods of Tungsten Alloy Tubes

As a key component of high-performance materials, the appearance quality and geometric dimensions of tungsten alloy tubes directly impact subsequent processing and final application performance. Rigorous and accurate appearance and dimensional testing are key to ensuring the quality of tungsten alloy tubes. The following details the main methods, key technical points, and practical applications for appearance and geometric dimensional testing of tungsten alloy tubes.

#### 1. Tungsten Alloy Tube Appearance Inspection Method

##### 1. Visual inspection (visual inspection)

- **Purpose of inspection** : To observe whether there are cracks, pores, inclusions, oxidation spots, scratches, deformation and other obvious defects on the surface of the pipe.
- **Methods and tools** :
  - Artificial vision combined with light source assistance (natural light or professional lighting);
  - Use a magnifying glass or microscope to assist in magnifying and observing subtle defects;
  - Combined with digital cameras or high-definition camera systems to achieve surface defect recording and analysis.
- **Inspection standards** : Determine the type and severity of defects based on product standards or customer requirements, and manage them in different levels.

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## 2. Surface gloss detection

- **Purpose of testing** : To evaluate the polishing or coating effect of tungsten alloy tube surface, and reflect the processing quality and surface condition.
- **Testing tool** : Gloss meter, which determines the surface finish grade by measuring the intensity of reflected light.

## 3. Surface profile and roughness detection

- **Purpose of testing** : To quantify surface micro-undulations and evaluate the effects of surface treatment processes.
- **Testing equipment** : roughness meter, profilometer and other precision instruments, capable of detecting roughness parameters such as Ra and Rz.

## 2. Tungsten Alloy Tube Geometric Dimensions Testing Method

tungsten alloy tubes include key dimensions such as outer diameter, inner diameter, wall thickness, length, concentricity, straightness and roundness. Common testing methods are as follows:

### 1. Outer and inner diameter measurement

- **Tools** : Vernier caliper, micrometer, bore gauge, coordinate measuring machine (CMM).
- **Notes** :
  - Use high-precision measuring tools to ensure that measurement errors are within the standard range;
  - The measuring points should be evenly distributed on different sections of the pipe to detect dimensional uniformity.

### 2. Wall thickness measurement

- **method** :
  - **Mechanical thickness gauge** : such as a micrometer, used to measure the wall thickness of the sample pipe;
  - **Ultrasonic thickness gauge** : non-contact measurement, suitable for online detection and complex structure pipes;
  - **X-ray inspection** : used for high-precision wall thickness and inner cavity shape analysis.
- **Application advantages** : Ultrasonic and X-ray methods are suitable for non-destructive testing to ensure that pipes have no internal defects.

### 3. Length measurement

- **Tools** : steel tape measure, laser rangefinder, etc.
- **Technical points** : Length measurement must ensure that the end surface of the pipe is flat to avoid measurement errors caused by irregular end surfaces.

### 4. Roundness and concentricity testing

- **Significance of detection** : Ensure the roundness of the pipe cross section and the concentricity of the inner and outer diameters to avoid uneven force during processing or use.

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- **Testing equipment** : roundness tester, coordinate measuring machine (CMM), which calculates roundness error and concentricity deviation by scanning the pipe cross section.

### 5. Straightness and curvature detection

- **Purpose of testing** : To confirm the linear shape of the pipe and prevent deformation that may cause difficulties in installation and use.
- **Testing method** : Use a straightness ruler, laser scanner or special curvature measuring instrument.

### 3. Testing Process and Quality Control

#### 1. Sampling principles

- Develop sampling plans in accordance with relevant standards (such as GB/T, ASTM) or customer agreements to ensure representativeness of testing.

#### 2. Testing environment

- Carry out the measurement in a constant temperature and humidity environment to reduce the impact of temperature and humidity on dimensional measurement.
- Prevent pollution and scratches and keep the pipe surface intact.

#### 3. Test data recording and analysis

- Establish a complete inspection data management system, including inspection results, defect types and location records.
- Statistically analyze the size fluctuation trend and adjust the production process in time.

#### 4. Judgment criteria

- Qualification is determined based on national standards, industry specifications or customer technical requirements.
- for non-conforming items to ensure that products meet design specifications.

### 4. Application of advanced detection technology

- **Coordinate Measuring Machine (CMM)** : Achieve high-precision three-dimensional measurement of complex geometric dimensions of tungsten alloy tubes with a high degree of automation.
- **Optical scanner** : quickly obtains three-dimensional morphological data of the pipe surface and cross section, suitable for pipes with complex shapes.
- **Machine vision system** : Combined with image recognition technology, it realizes automated appearance defect detection and classification.

### V. Summary

tungsten alloy tubes is fundamental to ensuring product quality. By employing a variety of advanced testing equipment and technologies, combined with a rational testing process and strict criteria, we can effectively guarantee the performance stability and reliability of tungsten alloy tubes during production and application. With the development of automated and intelligent testing technologies, quality control of tungsten alloy tubes will become even more precise and efficient in the future, providing a solid material guarantee for high-end applications.

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## 4.2 Density Test and Microstructure Density Characterization of Tungsten Alloy Tube

The density and microstructure of tungsten alloy tubes are important indicators of material quality and performance. High-density and high-microstructure tungsten alloy tubes typically exhibit excellent mechanical properties, wear resistance, and stable physical characteristics, making them widely used in high-end fields such as aerospace, nuclear industry, and military applications. Therefore, accurately testing the density of tungsten alloy tubes and characterizing their microstructure and microstructure are critical to ensuring product quality.

### 1. Density Test Method of Tungsten Alloy Tube

#### 1. Theoretical density calculation

- According to the mass fraction and density of each component in the tungsten alloy tube, the theoretical density of the alloy is obtained by weighted average calculation.
- The formula is:

$$\rho_{\text{theoretical}} = \sum (w_i \times \rho_i)$$

- where  $w_i$  is the mass fraction of each component, and  $\rho_i$  is the density of each component.
- Theoretical density is the density benchmark of a material under ideal conditions.

#### 2. Actual density measurement

- **Archimedean method :**
  - The buoyancy principle of water is used to measure the mass difference of the tungsten alloy tube in air and water, and its actual density is calculated.
  - Applicable to tungsten alloy tube samples with regular shape and measurable volume.
  - The measurement steps are simple and the accuracy is high, and it is widely used in laboratories and production sites.
- **Gas displacement method (pycnometer method) :**
  - The volume of the sample is replaced by gas (such as helium), which is suitable for samples with complex shapes or difficult to submerge in water.
- **X-ray diffraction (XRD) and CT scanning methods :**
  - Combined with high-precision instruments to obtain volume and mass data, it is suitable for high-end testing needs.

#### 3. Density Measurement Notes

- The sample must be kept clean and free of surface attachments.
- The measured ambient temperature and humidity must be stable to avoid errors.
- Multiple measurements were performed on multiple batches of samples, and the mean and standard deviation were calculated to ensure data reliability.

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## 2. Characterization Technology of Tungsten Alloy Tube Microstructure Density

### 1. Microstructure Observation

- **Optical Microscopy (OM) :**
  - Observe the microstructure after sintering, including grain size, grain boundary distribution and porosity.
  - It can qualitatively assess density and identify macroscopic pores and defects.
- **Scanning Electron Microscopy (SEM) :**
  - Provides high-resolution microscopic morphology images, capable of observing tiny pores, inclusions and grain boundaries.
  - Combined with energy dispersive spectrum analysis (EDS), the element distribution can be detected and the uniformity of the material can be determined.

### 2. Porosity Determination

- Image analysis software was used to quantitatively measure the porosity of microscopic images and calculate tissue density.
- Low porosity (high density) means better mechanical properties and stability.

### 3. X-ray computed tomography (CT)

- Non-destructive testing technology accurately detects the distribution, size and quantity of internal pores by reconstructing the internal structure of the pipe in three dimensions.
- High precision and high resolution, suitable for quality control of tungsten alloy tubes with complex shapes.

### 4. Correlation Analysis between Density and Compactness

- The ratio of actual density to theoretical density reflects the density level of tungsten alloy tube.
- The higher the density, the better the mechanical properties, thermal conductivity and service life of the material.
- By combining density testing with tissue characterization, we can guide process optimization and improve product quality.

## 3. Quality Control and Process Improvement Guidance

- Based on the density and compactness test results, the effects of sintering process parameters, raw material quality and powder properties on densification were analyzed.
- Adjust the sintering temperature, time and atmosphere, optimize the powder particle size distribution, and improve the overall density of the tube.
- Auxiliary technologies such as hot isostatic pressing (HIP) are used to further eliminate internal porosity and improve density and structural uniformity.

## IV. Summary

Density testing and microstructure characterization of tungsten alloy tubes are fundamental to ensuring product performance. Combining multiple testing methods and advanced characterization techniques allows for accurate assessment of material quality and guides continuous optimization of production processes. High-density tungsten alloy tubes not only enhance mechanical strength

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and corrosion resistance but also meet the material stability requirements of demanding applications, providing a solid foundation for high-end applications.

#### 4.3 Mechanical Properties Test Standards for Tungsten Alloy Tubes (ASTM, GB, ISO)

tungsten alloy tubes are directly related to the product's safety and service life. To ensure that the mechanical properties of tungsten alloy tubes meet design requirements, they must be systematically and rigorously tested according to internationally and domestically recognized standards. The primary standards used include those of the American Society for Testing and Materials (ASTM), the Chinese National Standard (GB), and the International Organization for Standardization (ISO).

##### 1. Key indicators of mechanical properties test of tungsten alloy tube

tungsten alloy tubes generally cover the following aspects:

- **Tensile Strength** : A measure of a material's ability to resist tensile failure.
- **Yield Strength** : The stress value at which the material begins to undergo plastic deformation.
- **Fracture Toughness** : The ability of a material to resist crack propagation.
- **Elongation** : The degree of plastic deformation of a material before it breaks under tension.
- **Hardness** : The ability of a material to resist local plastic deformation.
- **Fatigue Strength** : The ability of a material to withstand fracture under cyclic stress.
- **Compressive Strength** : The ability of a material to resist compression failure.

##### 2. Introduction to main test standards

###### 1. ASTM (American Society for Testing and Materials) standards

- **ASTM E8 / E8M** — "Standard Methods for Tensile Testing of Metallic Materials"  
specifies tensile testing methods for metallic materials, applicable to the tensile strength, yield strength, and elongation testing of tungsten alloy tube specimens. Key contents include specimen preparation, test equipment, test procedures, and data calculation methods.
- **ASTM E23** — "Standard Method for Impact Testing of Metallic Materials (Charpy Impact Test)"  
is used to evaluate the fracture toughness and impact properties of materials, and is particularly suitable for evaluating the toughness of tungsten alloy tubes.
- **ASTM E399** — "Metallic Materials Fracture Toughness Test Standard"  
measures the fracture toughness of materials and provides safe design parameters for high-end tungsten alloy tubes.
- **ASTM E466** — "Metallic Materials Fatigue Test Methods"  
evaluates the fatigue performance of tungsten alloy tubes and is particularly suitable for the cyclic loading requirements of the aerospace and military industries.

###### 2. GB (Chinese National Standard)

- **GB/T 228.1** — "Metallic Materials Tensile Test Methods at Room Temperature"  
This standard, similar to ASTM E8, specifies the requirements and methods for testing the

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tensile properties of tungsten alloy tubes and is widely used in domestic production and quality control.

- **GB/T 2975** — “Charpy impact test method for metallic materials”  
is used to determine the impact toughness of materials and ensure the crack resistance of tungsten alloy tubes.
- **GB/T 15248** — “Test method for fracture toughness of metallic materials”  
is suitable for quantitative analysis of the fracture toughness of tungsten alloy tubes.
- **GB/T 3075** — “Metallic materials fatigue test methods”  
evaluates the durability of materials under fatigue loading.

### 3. ISO (International Organization for Standardization)

- **ISO 6892-1** — “Metallic materials, tensile test methods”  
is applicable to the tensile strength and elongation testing of tungsten alloy tubes and complies with internationally unified test specifications.
- **ISO 148-1** — “Charpy impact test for metallic materials”  
standardizes the method for determining the impact resistance of materials.
- **ISO 12135** — “Metallic materials, test for fracture toughness”  
is an internationally recognized test for the fracture toughness of tungsten alloy tubes.
- **ISO 1099** — “Fatigue tests on metallic materials”  
is used to determine fatigue life and fatigue limit.

### 3. Specimen preparation requirements for mechanical properties testing

- The specimens should be processed in accordance with the shape and size specified in the relevant standards to ensure the accuracy and repeatability of the test results.
- Tungsten alloy tube samples generally need to be cut into test pieces of specified length to ensure that the cross section is complete and free of defects.
- The surface of the specimen should be properly treated, such as deburring and polishing, to reduce the influence of stress concentration on the test results.

### 4. Test equipment and environmental requirements

- Tensile, compression, impact and fatigue testing equipment should be calibrated to ensure accurate data.
- The test environment temperature and humidity should comply with the standard requirements, and normal temperature testing usually adopts room temperature of around 25°C.
- For high temperature mechanical property testing, a special high temperature testing device is required.

### 5. Data Processing and Quality Assessment

- Mechanical properties test data should be calculated according to standard methods, including indicators such as maximum load, yield point, and elongation.
- By comparing with the standard requirements, it is determined whether the tungsten alloy tube meets the design and use requirements.

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- Statistical analysis of multiple batches of samples helps in production process control and continuous improvement.

## VI. Summary

tungsten alloy tubes must strictly adhere to authoritative international and domestic standards such as ASTM, GB, and ISO to ensure a scientific testing process and accurate results. A comprehensive mechanical property testing system not only provides technical support for the design, production, and application of tungsten alloy tubes, but also provides a reliable basis for user safety and performance assurance. As tungsten alloy tube material performance continues to improve, relevant standards are also constantly being updated. The industry should continue to monitor standard developments to maintain technological leadership.

### 4.4 Metallographic Analysis and Microstructure Observation of Tungsten Alloy Tube

tungsten alloy tubes are important means to evaluate the internal structure of materials and control quality. They can intuitively reveal the microstructural characteristics, phase distribution, grain size, pore defects and other microscopic defects of the materials. They are of great significance for understanding the performance and failure mechanism of tungsten alloy tubes and optimizing process parameters.

#### 1. Purpose of Metallographic Analysis of Tungsten Alloy Tube

- **Observe the grain structure** : Evaluate the size, shape, and distribution of the grains. Grain refinement generally helps improve the mechanical properties of the alloy.
- **Analyze phase composition and distribution** : Identify different phases formed by elements such as tungsten, nickel, and iron , and determine the uniformity and phase stability of the alloy.
- **Detection of pores and inclusions** : Revealing the porosity and presence of non-metallic inclusions during the sintering process, which directly affect mechanical properties and density.
- **Observe the heat treatment effect** : Optimize the heat treatment process parameters by comparing the organizational changes before and after heat treatment.
- **Monitor micro cracks and deformation structures** : Analyze crack initiation locations and propagation paths to provide a basis for failure analysis.

#### 2. Sample Preparation Process

1. **Cutting and sampling** Take the cross-section and longitudinal section of the tungsten alloy tube sample , and use precision cutting equipment to avoid thermal effects and mechanical deformation.
2. **Mounting**  
: Mount the sample in resin to facilitate subsequent polishing and microscopic observation.

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### 3. Rough grinding and fine grinding

use sandpaper of different grits ( gradually grinding from coarse to fine, such as 400, 800, 1200, 2000 mesh) to remove surface saw marks and obtain a smooth surface.

### 4. Polishing:

Use diamond polishing agent (less than 1 $\mu$ m) for mirror polishing to eliminate grinding marks and improve surface finish.

### 5. Corrosion treatment

requires selecting an appropriate corrosive solution (such as a mixture of hydrofluoric acid and nitric acid) based on the chemical properties of the tungsten alloy. The corrosion time and concentration must be properly controlled to expose the grain boundaries and phase structure. The preparation and use of the corrosive solution must strictly adhere to safety operating procedures.

## 3. Microscopic Observation Techniques

### 1. Optical Microscopy (OM)

- Observe the overall grain structure, pore distribution, phase interfaces and macro defects.
- The microscopic morphology was understood through different magnifications, and the tissue uniformity was preliminarily analyzed.

### 2. Scanning Electron Microscopy (SEM)

- Provides high-resolution surface morphology images for detailed observation of grain boundaries, phase distribution and small defects.
- Combined with energy dispersive spectrum analysis (EDS) to achieve element qualitative and distribution analysis.

### 3. Transmission Electron Microscopy (TEM)

- Used to observe nanoscale organizational structures and reveal lattice defects, substructures and interface characteristics.
- It is usually used to study the distribution of fine strengthening phases and trace elements in tungsten alloy tubes.

### 4. X-ray diffraction (XRD)

- Analyze the phase composition and crystal structure of tungsten alloy tubes, detect changes in lattice parameters, and determine the stress state.

## 4. Relationship between microstructural characteristics and performance

- **Grain size** : Small and uniform grains help improve the strength and toughness of tungsten alloy tubes. Excessively large grains may lead to reduced performance.
- **Uniformity of phase distribution** : Uniformly distributed bonding phases such as nickel and iron help to enhance the plasticity and impact resistance of the alloy.
- **Porosity** : Low porosity means high density, which improves the mechanical properties and corrosion resistance of the alloy.
- **Inclusions and defects** : The presence of inclusions may become the starting point of cracks and reduce the service life of the material.

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- **Heat treatment effects** : Different heat treatment processes lead to grain growth, phase transformation or stress release, and microstructural changes directly reflect performance improvement or degradation.

## 5. The significance of metallographic analysis in practical applications

Tungsten alloy tubes are often faced with complex service conditions when used in aerospace, nuclear industry, medical equipment and other fields. Through metallographic analysis, we can:

- Quickly assess material quality and identify production defects.
- Guide process adjustments and optimize molding and heat treatment processes.
- Predict material service performance and lifespan, and provide early warning of failure.
- Support the research and development of new materials and verify the effects of modification technologies such as nano-strengthening and micro-alloying.

## VI. Summary

tungsten alloy tubes are crucial tools for gaining a deeper understanding of material properties and ensuring quality control. Combined with advanced microscopy techniques, these techniques provide a scientific microscopic foundation and technical support for the research, development, production, and application of tungsten alloy tubes. In the future, with the continuous advancement of microanalysis techniques, the microstructural study of tungsten alloy tubes will become even more detailed, laying a solid foundation for the design and manufacture of high-performance tungsten alloy tubes.

## 4.5 Chemical Composition and Impurity Testing of Tungsten Alloy Tubes (ICP, XRF, ONH)

tungsten alloy tubes are key factors in determining their physical and mechanical properties. Accurate and reliable chemical composition analysis ensures a reasonable material ratio and uniform composition, while also preventing the negative impact of harmful impurities on alloy properties. Commonly used testing techniques include inductively coupled plasma optical emission spectrometry (ICP), X-ray fluorescence spectrometry (XRF), and oxygen, nitrogen, and hydrogen analyzers (ONH). These are respectively suitable for the detection of different elements and impurities, complementing each other and forming the core system for chemical composition quality control of tungsten alloy tubes.

### 1. ICP (Inductively Coupled Plasma Optical Emission Spectrometry)

#### Principles and Applications:

ICP excites atoms or ions in a sample, causing them to emit spectral lines of characteristic wavelengths. The intensity of these spectral lines is then used to determine elemental concentrations. This method offers high sensitivity and the ability to simultaneously detect multiple elements, making it suitable for the accurate analysis of both major and trace elements in tungsten alloy tubes.

#### Test content

- Main elements: tungsten (W), nickel (Ni), iron (Fe), molybdenum (Mo), etc.

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- Trace elements: copper (Cu), cobalt (Co), manganese (Mn), chromium (Cr), etc.
- Impurity elements: harmful impurities such as sulfur (S), phosphorus (P), lead (Pb), and cadmium (Cd).

#### Advantages

- High sensitivity, capable of detecting trace elements at the ppm level.
- The analysis speed is fast and suitable for batch testing.
- Simultaneous detection of multiple elements saves time.

#### Sample Preparation:

Tungsten alloy tube samples usually need to be dissolved in acid or melted to make a solution to ensure sample uniformity and avoid element loss.

## 2. XRF (X-ray fluorescence spectrometry)

#### Principles and Applications:

XRF uses high-energy X-rays to excite elements in a sample, causing them to emit characteristic fluorescent X-rays. The energy and intensity of the fluorescent X-rays are used for qualitative and quantitative elemental analysis. It is suitable for rapid elemental composition analysis of tungsten alloy tubes, particularly for solid sample testing.

#### Test content

- Main alloying elements: tungsten, nickel, iron, copper, etc.
- Detection capabilities for some light elements are limited.

#### Advantages

- Sample preparation is simple and does not require complex dissolution.
- Non-destructive testing keeps the sample intact.
- Suitable for on-site rapid detection and process control.

#### limitation

- The detection of light elements (such as oxygen, nitrogen, and hydrogen) is weak.
- The detection sensitivity is slightly lower than that of ICP, making it difficult to detect extremely trace impurities.

## 3. ONH (Oxygen, Nitrogen and Hydrogen Analyzer )

#### Principle and Application:

The ONH analyzer measures the oxygen, nitrogen, and hydrogen content of a gas by melting a sample at high temperature. It is suitable for the precise determination of these light elements in tungsten alloy tubes. Oxygen, nitrogen, and hydrogen have a significant impact on the mechanical properties, corrosion resistance, and thermal stability of tungsten alloy tubes.

#### Test content

- Oxygen content (O)

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- Nitrogen content (N)
- Hydrogen content (H)

#### Advantages

- The measurement is sensitive and accurate.
- Indispensable for light element and impurity content detection.

#### Sample preparation

usually requires taking a small piece of tungsten alloy tube sample, placing it in a high-temperature furnace to melt it, and then analyzing the gas after release through the detection system.

### 4. Comprehensive Analysis and Quality Control

tungsten alloy tubes is often combined with ICP, XRF and ONH technology to form a multi-angle and multi-level composition analysis system. Through these methods, we can:

- Ensure that the content of main alloy elements meets the designed ratio.
- Accurately monitor the level of harmful impurities to prevent them from affecting performance.
- Control light elements such as oxygen, nitrogen and hydrogen to ensure high performance and high stability of materials.
- Promote process optimization and improve product consistency.

### V. Conclusion

tungsten alloy tubes is fundamental to ensuring product quality. Advanced testing technologies such as ICP, XRF, and ONH enable highly accurate and efficient composition analysis, providing solid data support for performance assurance, process control, and technological research and development. With the continuous advancement of analytical instrumentation, future testing will be even more accurate and rapid, safeguarding the high-quality development of the tungsten alloy tube industry.

### 4.6 Evaluation Method for Wall Thickness Uniformity and Coaxiality of Tungsten Alloy Tubes

tungsten alloy tubes require wall thickness uniformity and coaxiality, which are key indicators for ensuring the tube's mechanical properties, operational safety, and processing accuracy. Wall thickness uniformity is related to the tube's strength distribution and pressure resistance, while coaxiality directly affects the tube's assembly accuracy and mechanical matching performance. Scientific and accurate evaluation methods are crucial for tungsten alloy tube quality control and process optimization.

#### 1. Wall thickness uniformity evaluation method

##### 1. Ultrasonic Thickness Measurement

- **Principle** : The time difference of ultrasonic wave propagation in tungsten alloy tube wall is used to measure the tube wall thickness.
- **Advantages** :
  - Non-destructive testing.

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- The measurement speed is fast and multi-point rapid scanning can be achieved.
- Suitable for on-site and online testing.
- **Implementation :**
  - Apply coupling agent on the pipe surface to ensure ultrasonic coupling.
  - Use a portable or automated ultrasonic thickness gauge to measure the wall thickness at multiple preset points.
  - After data collection, statistical analysis is performed to calculate wall thickness uniformity indicators (such as maximum-minimum difference, standard deviation, etc.).

## 2. X-ray or gamma-ray fluoroscopy (Radiographic Thickness Measurement)

- **Principle :** The radiation penetrates the pipe and the change in the intensity of radiation absorption reflects the change in the pipe wall thickness.
- **Advantages :**
  - Can detect wall thickness and internal defects simultaneously.
  - Strong adaptability to complex-shaped pipes.
- **Limitations :**
  - The equipment cost is high.
  - Radiation protection measures are required.
- **application :**
  - Suitable for high-precision wall thickness distribution detection and quality control in the R&D stage.

## 3. Mechanical measurement (mechanical calipers, coordinate measuring machines)

- **Principle :** Measure the inner and outer diameters of the pipe through mechanical contact and calculate the wall thickness.
- **advantage :**
  - Simple and intuitive, suitable for large pipe sizes.
- **insufficient :**
  - The sample needs to be disassembled, which may damage the surface.
  - The measurement points are limited, making it difficult to fully reflect the uniformity of wall thickness.

## 2. Coaxiality evaluation method

Coaxiality refers to the relative position accuracy between the inner diameter and outer diameter of the tungsten alloy tube, reflecting the geometric accuracy and processing quality of the tube.

### 1. Coordinate Measuring Machine (CMM)

- **Principle :** Use a 3D measuring probe to collect point cloud data of the inner and outer surfaces of the pipe, and calculate the coaxiality through software.
- **Advantages :**
  - High-precision measurement.
  - Detailed geometric deviation reports can be output.
  - Suitable for complex pipes and strict tolerance requirements.
- **step :**

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- Set up the measurement program and collect multiple points of the inner and outer diameters as required.
- The software fits the cylindrical shape and calculates the axis deviation between the two.

## 2. Inner and outer diameter measurement method

- **method :**
  - Measure the multi-point diameter values of the inner diameter and outer diameter of the pipe respectively.
  - The deviation of the center lines of the two cylinders is estimated by mathematical methods.
- **applicability :**
  - Suitable for rapid on-site assessments.
  - Accuracy is limited by the measuring tool.

## 3. Optical measurement technology

- **laser scanners and image measuring instruments** can realize non-contact coaxiality detection.
- Advantages include high precision, non-destructiveness, and suitability for thin-walled or precision tungsten alloy tubes.

## 3. Data Analysis and Evaluation Indicators

- **Wall thickness uniformity index :**
  - Maximum wall thickness difference (Max-Min)
  - Standard deviation ( $\sigma$ )
  - Uniformity coefficient (uniformity percentage)
- **Coaxiality index :**
  - Axis offset (  $\mu\text{m}$  level)
  - Tolerance compliance rate (whether it meets the design tolerance requirements)

## 4. Quality Control Recommendations

- It is recommended to establish an online detection system for wall thickness and coaxiality to achieve real-time monitoring.
- Regularly calibrate measuring equipment to ensure accurate test data.
- Based on the test results, feedback is given to process adjustments, mold design and forming process are optimized, and the overall quality of tungsten alloy tubes is improved.

## V. Summary

Wall thickness uniformity and coaxiality are core quality indicators for tungsten alloy tubes. Using a variety of techniques, including ultrasonic thickness measurement, radiographic testing, three-dimensional coordinate measurement, and optical measurement, we can achieve a comprehensive and accurate evaluation of tungsten alloy tubes, providing solid data support for product performance assurance and process improvement.

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#### 4.7 Surface and Inner Wall Defect Detection Technology of Tungsten Alloy Tubes (Eddy Current, CT, Ultrasonic)

tungsten alloy tubes face surface and internal defects that directly impact their mechanical properties, service life, and safety. Therefore, employing high-precision nondestructive testing techniques to inspect these tubes for surface and internal defects is crucial for quality control and performance assurance. The following details the applications and advantages of eddy current testing, computed tomography (CT), and ultrasonic testing for defect detection in tungsten alloy tubes.

##### 1. Eddy Current Testing (ECT)

###### 1. Principle Introduction

Eddy current testing uses the principle of electromagnetic induction to identify surface cracks, pits, corrosion and other defects by detecting changes in induced eddy currents on the pipe surface and near-surface conductive materials.

###### 2. Advantages of using tungsten alloy tubes

- **High sensitivity** : Very sensitive to minute surface cracks and corrosion, capable of detecting sub-millimeter defects.
- **Fast scanning** : suitable for fast non-destructive testing, and can realize online testing in mass production.
- **Non-contact detection** : avoids damage to the pipe surface.
- **Suitable for complex geometries** : Different probe designs can be used to detect the inner wall of the pipe and complex parts.

###### 3. Limitations

- The detection depth is limited, making it difficult to detect deep internal defects.
- Some knowledge of the electromagnetic properties of the material is required to adjust the detection parameters.

##### 2. Computed Tomography (CT)

###### 1. Principle Introduction

CT uses X-rays to rotate around the pipe to collect multi-angle projection images, and reconstructs the three-dimensional internal structure of the pipe through a computer, achieving intuitive imaging of internal and external defects.

###### 2. Advantages of using tungsten alloy tubes

- **Three-dimensional imaging capability** : can accurately display the defect location, size, shape and spatial distribution.
- **High resolution** : suitable for detecting internal defects such as fine cracks, pores, inclusions, etc.
- **Non-destructive** : No need to destroy the sample, suitable for quality assessment of high-value tungsten alloy tubes.
- **Multifunctional testing** : In addition to defect detection, it can also perform structural integrity analysis and geometric dimension testing.

###### 3. Limitations

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- Equipment investment and maintenance costs are high.
- The detection cycle is long and it is not suitable for online detection of high-speed production lines.
- For high-density materials such as tungsten alloy, the radiation energy needs to be adjusted to ensure penetration.

### 3. Ultrasonic Testing (UT)

#### 1. Principle Introduction

Ultrasonic testing uses high-frequency sound waves to propagate through pipes and encounter sound wave signals reflected or scattered by defects to detect internal defects.

#### 2. Advantages of using tungsten alloy tubes

- **Strong penetration ability** : suitable for detecting deep defects inside pipes, such as cracks, pores, inclusions and interlayer separation.
- **Multiple detection methods** : including pulse echo method and phased array technology to meet the detection needs of different defect types.
- **Online detection is possible** : suitable for rapid detection of production lines.
- **Non-destructive testing** : no damage to the pipe.

#### 3. Limitations

- It is sensitive to surface conditions and requires a good coupling agent to ensure detection quality.
- The sound waves in high-density materials are attenuated more, and the frequency and power need to be adjusted to achieve the best effect.

### 4. Comprehensive Detection Strategy

In order to ensure the quality and safety of tungsten alloy tubes, a combination of various testing technologies is usually used:

- **Eddy current testing** is used to quickly screen for surface and near-surface defects.
- **Ultrasonic testing** can deeply detect internal defects of pipe walls, especially for medium and thick pipes.
- **CT scanning** is used for high-precision defect imaging and quantitative analysis of complex defects.

This multi-level, multi-technology collaborative detection system effectively improves the comprehensiveness and accuracy of detection.

### 5. Summary:

Surface and interior defect detection for tungsten alloy tubes relies on advanced nondestructive testing technologies such as eddy current, CT, and ultrasound to fully understand defects of varying types and depths. With the continuous upgrading and intelligent development of testing equipment, defect detection for tungsten alloy tubes will become more efficient and accurate in the future, safeguarding the stable production and application of high-performance tungsten alloy tubes.

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**Precision customization:** support high density (17-19 g/cm<sup>3</sup>), special performance, complex structure, super large and very small parts design and production.

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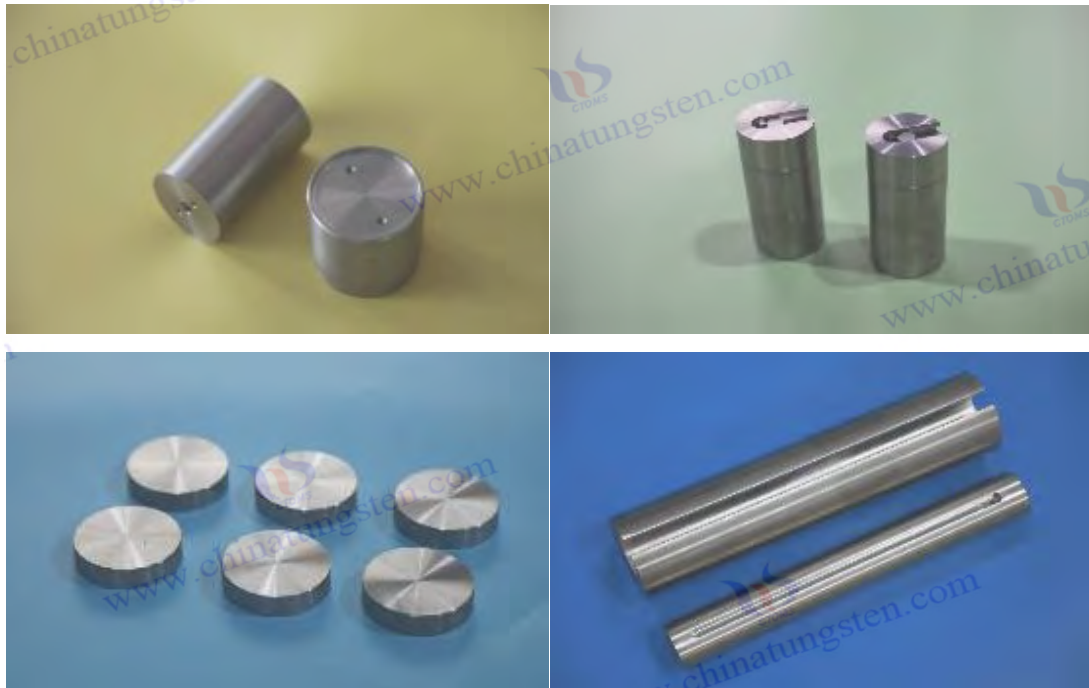
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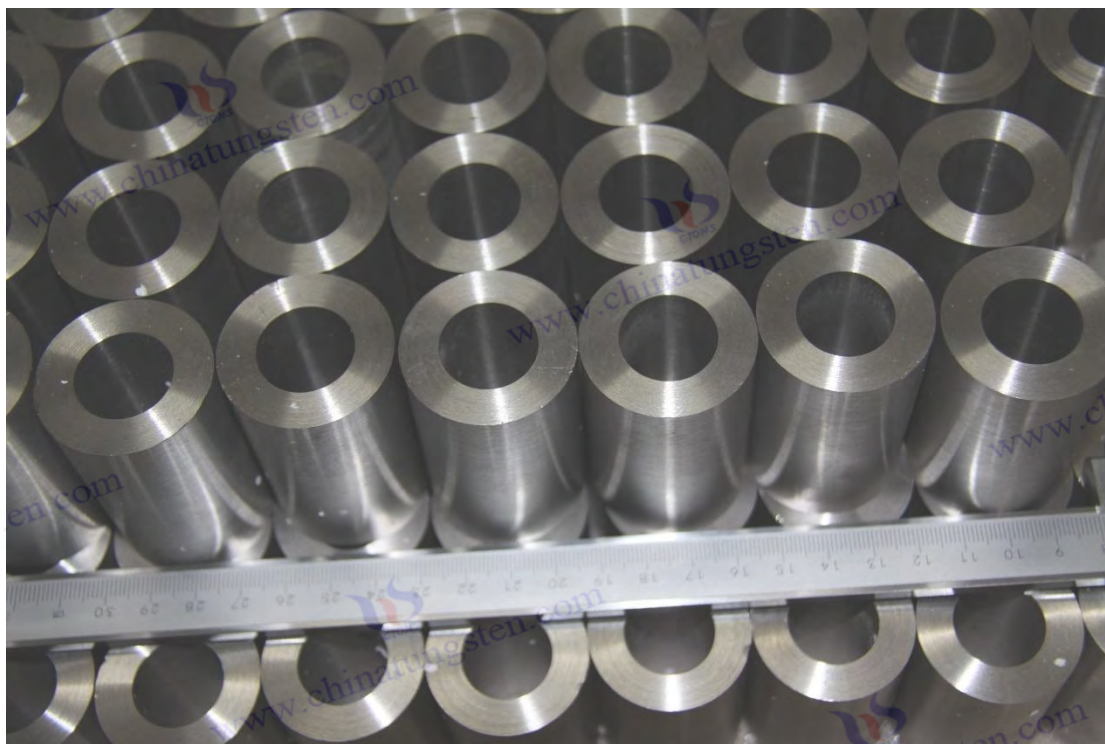
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电话/TEL: 0086 592 512 9696  
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## Chapter 5 Typical Application Fields of Tungsten Alloy Tube

### 5.1 Application of tungsten alloy tubes in shielding and structural casing in the nuclear industry

Tungsten alloy tubes, with their extremely high density, excellent radiation resistance, and good mechanical strength, play an irreplaceable and important role in the nuclear industry, particularly in radiation shielding and structural casing. The following details the key applications and technical advantages of tungsten alloy tubes in the nuclear industry.

#### 1. Advantages of tungsten alloy tubes as nuclear radiation shielding materials

In nuclear industrial environments, radioactive radiation poses a significant threat to both personnel safety and equipment operation. The high density (typically exceeding  $17.0 \text{ g/cm}^3$ ) and atomic number (74) of tungsten alloy tubes provide them with strong gamma-ray and X-ray shielding capabilities, effectively reducing radiation transmittance and protecting the safety of nuclear reactors, nuclear fuel assemblies, and operators.

- **High-density shielding** : The shielding efficiency of tungsten alloy tube is better than that of traditional lead and steel materials, and it has better mechanical properties and environmental adaptability.
- **High mechanical strength** : Maintains excellent structural stability even in high temperature and high pressure environments.
- **Good corrosion resistance** : suitable for complex chemical environments and radiation fields in the nuclear industry.

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## 2. Application of Tungsten Alloy Tube in Structural Casing in Nuclear Industry

In nuclear reactors and related equipment, tungsten alloy tubes are often used as structural casings to protect and support key components within the equipment. Specific applications include:

- **Coating of nuclear fuel assemblies** : Tungsten alloy tubes can be used as fuel rod cladding to prevent leakage of radioactive materials and enhance the mechanical integrity of fuel assemblies.
- **Neutron Absorbing Tube** : By optimizing the alloy composition, the tungsten alloy tube can effectively absorb neutrons, regulate the nuclear reaction rate, and improve the safety performance of the reactor.
- **Reactor cooling system pipes** : Taking advantage of its high temperature resistance, high strength and corrosion resistance, tungsten alloy tubes are used in nuclear reactor coolant pipes to ensure stable operation of the system.

## 3. Technical requirements of tungsten alloy tubes in nuclear industry

For nuclear industry applications, tungsten alloy tubes must meet the following key technical indicators:

- **High density and low porosity** ensure shielding performance and mechanical strength.
- **Strict dimensional accuracy** ensures precise assembly and sealing in nuclear equipment.
- **The radiation resistance is stable and** the material performance remains unchanged after long-term radiation .
- **It has strong corrosion and heat resistance** and is suitable for high temperatures and corrosive media in nuclear environments.

## 4. Typical Application Cases of Tungsten Alloy Tubes in Nuclear Industry

- **Reactor neutron absorption tube** : A nuclear power plant uses W-Ni-Fe tungsten alloy tubes as neutron absorption materials, which significantly improves the control accuracy and safety factor of the reactor.
- **Nuclear waste storage container lining tube** : Tungsten alloy tube is used as the lining of nuclear waste container to effectively prevent radiation leakage and ensure environmental safety.
- **Radioactive equipment protective shield** : Shields made of tungsten alloy tubes are used to protect nuclear industry operators from radiation damage.

## V. Future Development Direction

With the development of nuclear industry technology, the application requirements of tungsten alloy tubes are becoming increasingly diversified. Future research focuses include:

- **high-performance tungsten alloy tube** reduces the structural burden while ensuring the shielding effect.
- **Nanostructure optimization of tungsten alloy tubes** improves their mechanical and radiation resistance properties.

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- **Intelligent monitoring and quality control technology** ensures the long-term stable operation of tungsten alloy tubes in nuclear environments.

## VI. Summary

tungsten alloy tubes play a central role in ensuring nuclear safety and equipment stability due to their excellent physical properties and environmental resistance. In the future, with the continuous advancement of materials science and manufacturing technology, tungsten alloy tubes will show broader application prospects in the nuclear energy field.

## 5.2 Structure and Protection Function of Tungsten Alloy Tube in Military Weapon Systems

Tungsten alloy tubes, with their high density, high strength, and excellent heat and corrosion resistance, play a vital structural and protective role in modern military weapon systems. These key advantages make them an ideal material for the manufacture of core components in a variety of weapon systems, with applications in a wide range of fields, including projectile casings, missile casings, armor-piercing armor, and protective barriers.

### 1. Structural Advantages of Tungsten Alloy Tubes in Military Weapon Systems

#### 1. **high**

mechanical strength and hardness, which can withstand extreme shock loads and vibration environments, ensuring the structural integrity of weapon systems during launch, flight, and explosions. Its excellent fatigue resistance ensures the long-term reliability of weapon components.

#### 2. **density**

of tungsten alloy tubes (usually above 17.0 g/cm<sup>3</sup>) makes them an ideal inertial counterweight material. They are widely used in attitude control systems and ballistic stabilization devices of missiles and aircraft to improve the accuracy and stability of weapons.

#### 3. **Excellent thermal stability**

In high temperature, explosive and high-speed flight environments, tungsten alloy tubes can maintain good thermal stability and mechanical properties, preventing structural failure due to thermal expansion or softening.

### 2. Application of Tungsten Alloy Tube's Protective Function

#### 1. Tungsten alloy tubes are often used as **casing materials for armor-piercing**

projectiles due to their high hardness and density. Tungsten alloy tubes can effectively concentrate the bullet energy, improve the ability to penetrate armor, and enhance the lethality of armor-piercing projectiles.

#### 2. **and rocket**

body structures, which not only improve the mechanical strength and stability of the body, but also effectively reduce the structure volume to achieve high-performance lightweight design.

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### 3. Protective armor and barrier materials

As a high-density protective material, tungsten alloy tubes can be made into protective pipe fittings and installed in key parts of important military facilities and vehicles to enhance their resistance to elasticity and explosion impact.

### 3. Technical requirements of tungsten alloy tubes in the military field

- **Density and uniformity**  
ensure that the pipe is free of pores and inclusions, improving the overall mechanical properties and impact resistance.
- **The dimensional accuracy and geometric coaxiality**  
meet the high requirements of complex weapon system assembly and ensure the precise fit of mechanical interfaces.
- **The corrosion resistance and wear resistance**  
adapt to the changing military environment and extend the service life of weapon system components.
- **Radiation resistance and thermal stability**  
meet the requirements of high temperature and high radiation combat environments, maintaining stable material properties.

### 4. Typical Application Cases

- A certain type of advanced armor **-piercing projectile with a core and casing uses a** tungsten alloy tube as the core casing, successfully penetrating multi-layer composite armor and significantly improving the ammunition's lethality.
- High-precision tungsten alloy tubes **for missile inertial counterweights** are used as inertial counterweights in missile attitude control systems, ensuring the stability of the missile's flight trajectory and its accuracy.
- **the armored vehicle's protective layer**  
, tungsten alloy tubes for armored vehicle protection enhance the vehicle's anti-explosion and anti-penetration capabilities, and improve occupant safety.

### 5. Future Development Trends

#### The design of

**high-performance tungsten alloy tube materials** combines nano-strengthening and micro-alloying technologies to improve the comprehensive performance of the material and meet the future demand for high strength and high toughness.

- **Intelligent manufacturing and precision processing technology**  
uses advanced manufacturing technologies such as 3D printing and laser processing to achieve the preparation of tungsten alloy tubes with complex shapes and improve the overall performance of weapon systems.
- **composite structure tungsten alloy tubes**  
Composite tubes made of tungsten alloy and other functional materials are developed to

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achieve multi-functional integration and enhance the protection and combat capability of weapon systems.

## VI. Summary

Tungsten alloy tubes are irreplaceable in the structural and protective functions of military weapon systems. Their high density, high strength, and excellent environmental resistance provide a solid foundation for modern weapon systems. With advances in materials science and manufacturing processes, tungsten alloy tubes will demonstrate broader application prospects and technological advantages in the military sector.

### 5.3 Protection and Positioning of Tungsten Alloy Tubes in Medical Radiotherapy Equipment

Tungsten alloy tubes, with their exceptional high density and shielding properties, play a key role in the protection and positioning of medical radiotherapy equipment. During radiotherapy, precise radiation exposure and the safe protection of personnel and equipment are crucial to both treatment effectiveness and operational safety. Tungsten alloy tubes, due to their unique physical properties, are widely used in the design and manufacture of related equipment.

#### 1. High-density shielding performance advantages of tungsten alloy tubes

##### 1. effectively block high-energy radiation

The density of tungsten alloy tubes is usually above  $17.0 \text{ g/cm}^3$ . They have higher radiation attenuation ability than traditional shielding materials such as lead. They can effectively block high-energy radiation such as X-rays and gamma rays, reduce radiation leakage, and ensure the safety of patients and operators.

##### 2. Optimize equipment volume and weight.

Compared with traditional lead materials, tungsten alloy tubes have smaller size and more compact structure while achieving the same protective effect. This helps to design lightweight and flexible radiotherapy equipment, and improves the ease of use and durability of the equipment.

#### 2. Typical Applications of Tungsten Alloy Tubes in Radiotherapy Equipment

##### 1. Tungsten alloy tubes are often used as sheath materials for the

beam outlet of radiotherapy equipment to precisely control the direction and intensity of the radiation, avoid radiation scattering and unnecessary tissue exposure, and improve treatment accuracy.

##### 2. Radiation protection cover and shielding assembly

The built-in tungsten alloy control shield is used to protect key electronic components and operators, prevent radiation leakage from the equipment, and ensure stable operation of the equipment and a safe operating environment.

##### 3. in patient positioning support structures

make them an important structural material for patient positioning devices, ensuring accurate positioning of patients during radiotherapy and improving treatment outcomes.

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### 3. Physical performance requirements of tungsten alloy tube

- **High density and uniformity**  
ensure the continuity and stability of the protection effect, avoiding the decline of shielding effect due to material defects.
- **Dimensional accuracy and surface quality**  
ensure the precise fit of the internal structure of radiotherapy equipment, improving the overall stability and durability of the equipment.
- **Good thermal stability and corrosion resistance**  
can adapt to the high temperature environment and cleaning and disinfection requirements during equipment operation, extending the service life of components.

### IV. Development Trends and Technological Innovation

- **functionally graded tungsten alloy tubes**  
achieves optimal performance of tungsten alloy tubes in different locations through gradient design of material composition and organizational structure, taking into account both shielding efficiency and mechanical strength.
- **tungsten alloy tubes and intelligent monitoring systems combined**  
with sensing technology enables real-time monitoring of the protection status within radiotherapy equipment, improving equipment safety and reliability.
- **additive manufacturing technology**  
uses 3D printing technology to customize tungsten alloy tube components with complex shapes to meet the design needs of personalized medical equipment.

### V. Summary

Tungsten alloy tubes, with their exceptional high density and mechanical properties, play an irreplaceable role in the protection and positioning of medical radiotherapy equipment. In the future, with the continuous advancement of material technology and manufacturing processes, tungsten alloy tubes will have greater potential in improving the performance and safety of medical equipment, contributing to the development of precision medicine.

### 5.4 Tungsten Alloy Tubes for Inertial Parts and High-Temperature Flow Tubes in Aerospace

Tungsten alloy tubes, due to their high density, high strength, and excellent high-temperature performance, play a key role in inertial components and high-temperature flow ducts in the aerospace industry. These applications place extremely high demands on the material's physical and mechanical properties and environmental adaptability. Tungsten alloy tubes can meet these stringent conditions, ensuring the stability and safety of aircraft and engine systems.

#### 1. Advantages of Tungsten Alloy Tubes as Aerospace Inertial Parts

##### 1. High density leads to high inertia.

Tungsten alloy tubes typically have a density between 17-19 g/cm<sup>3</sup>, making them an ideal

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counterweight material. Inertial components such as gyroscope counterweights and balance weights in inertial navigation systems utilize tungsten alloy tubes to achieve high mass concentration, thereby improving system stability and accuracy.

2. **Excellent mechanical strength and toughness**

Aerospace inertial parts need to withstand severe vibration and impact loads. Tungsten alloy tubes have excellent tensile strength, yield strength and toughness, ensuring that the parts will not break or deform under extreme vibration environments.

3. **Dimensional stability and processing precision**

High dimensional precision and excellent thermal stability enable tungsten alloy tube inertial components to maintain structural stability in complex environments, ensuring the accurate operation of the inertial navigation system.

2. **Application Value of Tungsten Alloy Tube in High-Temperature Flow Guide Tube**

1. **with excellent high temperature resistance**

maintain good mechanical properties and chemical stability in high temperature environments. They are suitable for use as guide tubes in key areas such as aircraft engine combustion chambers and high-temperature exhaust systems to ensure the stability and efficiency of gas flow.

2. **Thermal fatigue resistance and thermal expansion matching:**

Tungsten alloy tubes have a low thermal expansion coefficient and can match well with other high-temperature alloy materials, reducing cracks and fatigue caused by thermal stress and extending the service life of the guide tube .

3. **Excellent corrosion resistance:**

The fuel gas environment in aircraft engines is complex and contains a variety of corrosive gases. Tungsten alloy tubes have excellent anti-oxidation and anti-corrosion properties, ensuring the long-term stable operation of the guide tube .

3. **Manufacturing Technology of Tungsten Alloy Tube in Aerospace Applications**

1. **Advanced powder metallurgy forming technology produces high-density**

tungsten alloy tubes through isostatic pressing, die pressing and other technologies , combined with precision sintering and heat treatment to obtain excellent mechanical properties and dense microstructure.

2. **High-precision machining and surface treatment**

use precision grinding, polishing and surface coating technologies to ensure that the tube size and surface quality meet the stringent requirements of aerospace components.

3. **Additive manufacturing technology exploration**

combines additive manufacturing technology to achieve rapid prototyping of complex-shaped tungsten alloy tube components to meet customized and diversified design needs.

IV. **Future Development Trends and Challenges**

• **Functional integration and lightweight design**

explore the combination of tungsten alloy tubes and composite materials, optimize the

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structural design of inertial parts and guide tubes , and achieve a balance between high performance and lightweight.

- **Improved performance in high temperature environments**

Through microalloying and nanostructure design, the high temperature resistance and thermal stability of tungsten alloy tubes are further improved to meet the needs of future extreme aerospace environments.

- **Intelligent monitoring and life prediction**

integrate sensor technology to monitor the status of tungsten alloy tube components in real time, predict fatigue life, and ensure the safety and reliability of aerospace systems.

## V. Summary

Tungsten alloy tubes, with their unique physical and mechanical properties, have broad application prospects in aerospace inertial components and high-temperature flow guide tubes . With the continuous advancement of materials science and manufacturing technology, tungsten alloy tubes will continue to promote the development of aerospace technology, achieving higher performance and safety.

## 5.5 Application of Tungsten Alloy Tubes as Heat Dissipation Pipes in Electronic and Communication Equipment

As electronic and communication equipment develops towards high performance, high integration, and miniaturization, heat dissipation becomes a key factor restricting the stability and lifespan of the equipment. Tungsten alloy tubes, with their excellent thermal conductivity, high density, and good mechanical strength, have become an ideal heat dissipation pipe material in the electronics and communications fields.

### 1. Material Advantages of Tungsten Alloy Tube Heat Dissipation Pipe

1. **with high thermal conductivity**

have high thermal conductivity and can quickly transfer the heat generated by electronic components to the heat sink or the external environment, avoiding local overheating and ensuring the normal operation of the equipment.

2. **Excellent thermal expansion matching:**

The thermal expansion coefficient of tungsten alloy is close to that of many semiconductor and electronic materials, which reduces poor contact and material fatigue caused by thermal stress and improves the stability of the heat dissipation system.

3. **Mechanical stability brought by high density**

The high density of tungsten alloy tubes gives them good mechanical strength and vibration resistance, allowing them to maintain structural integrity under equipment vibration or impact environments.

4. **Chemical stability and corrosion resistance:**

In a changing electronic environment, tungsten alloy tubes are not easily oxidized or corroded, ensuring long-term and reliable use of heat dissipation pipes.

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## 2. Specific Applications of Tungsten Alloy Tubes in Electronic and Communication Equipment

### 1. Heat dissipation of high-power semiconductor devices

Power amplifiers, RF modules and other high-power semiconductor devices generate a lot of heat. Tungsten alloy tubes are used as heat conduction paths to improve heat dissipation efficiency and prevent performance degradation caused by excessive temperature.

### 2. Heat dissipation of communication base station equipment

Amplifiers, processing units and other key equipment in communication base stations require a stable heat dissipation system. Tungsten alloy tubes can effectively transfer heat to ensure continuous and stable operation of the equipment.

### 3. Tungsten alloy tubes are used as cooling conduits in high-end electronic instruments such as lasers and sensors to maintain device temperature stability, improve measurement accuracy and instrument life .

### 4. Micro heat dissipation structure integrated

tungsten alloy tube can be made into micro heat pipe through micromachining technology, which is used for local heat dissipation of high-density integrated circuits and meets the extreme requirements of microelectronic devices for heat dissipation performance.

## 3. Manufacturing and Technical Challenges of Tungsten Alloy Tube Heat Dissipation Pipes

### 1. High-precision dimensional control

The heat dissipation ducts of electronic equipment must strictly control the size and wall thickness to ensure efficient matching with other heat dissipation components. Tungsten alloy tubes must undergo precision processing and testing.

### 2. The smoothness of the inner and outer surfaces requires that

the inner wall be smooth to facilitate the smooth flow of fluids (such as coolant) and reduce resistance, while the outer surface finish affects the heat dissipation efficiency and contact performance.

### 3. Composite materials and coating technology

For different application environments, the surface of tungsten alloy tubes may need to be coated to enhance thermal conductivity, corrosion resistance or electrical insulation to achieve multifunctional composites.

## IV. Future Development Trends

### • The intelligent cooling system

integrates sensors and intelligent control to achieve real-time temperature monitoring and adjustment of the tungsten alloy tube heat dissipation duct, improving system response speed and cooling efficiency.

### • Microstructure design optimization

utilizes advanced material design and micromachining technology to optimize the internal structure of tungsten alloy tubes to achieve higher heat transfer efficiency and mechanical properties.

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- **The development of lightweight and high-performance composite materials improves the comprehensive performance of** tungsten alloy tubes through technologies such as nanoparticle reinforcement and gradient functional design to meet the needs of electronic equipment for lightweight and high reliability.

## V. Summary

Tungsten alloy tubes, with their excellent thermal conductivity, mechanical strength, and environmental adaptability, are ideal materials for heat dissipation pipes in electronic and communication equipment. As electronic equipment performance continues to improve and heat dissipation technology advances, the application scope of tungsten alloy tubes will continue to expand, driving the steady development of high-performance electronic products.

## for Structural Support in Industrial Molds and Wear-Resistant Liners

Tungsten alloy tubes are widely used in industrial molds and wear-resistant liners due to their high density, high hardness and excellent wear resistance. They play a key role in structural support and wear protection, effectively improving mold life and equipment operation stability.

### 1. The material advantages of tungsten alloy tubes are reflected in industrial molds

#### 1. High Hardness and Wear Resistance

Tungsten alloy tubes have extremely high hardness and wear resistance. They can withstand the high pressure and high friction of materials during the mold forming process, significantly extending the service life of the mold and reducing the cost of frequent replacement or maintenance.

#### 2. High Density and Mechanical Strength

The high density of tungsten alloy tubes gives them excellent mechanical strength and deformation resistance, ensuring that the mold maintains structural stability and dimensional accuracy under high load and high impact conditions.

#### 3. Good thermal stability:

Industrial molds often work at high temperatures. Tungsten alloy tubes have excellent high temperature resistance, can effectively resist thermal fatigue and thermal expansion, and reduce the impact of thermal deformation on mold forming quality.

### 2. The key role of tungsten alloy tube in wear-resistant liner

#### 1. Structural support

**of wear-resistant liner:** Tungsten alloy tube is the core bearing material of wear-resistant liner, providing strong structural support to ensure the stability of liner in high-speed and high-wear environment, and reduce leakage and damage caused by pipeline wear.

#### 2. Corrosion resistance and chemical stability

In harsh environments such as chemical and mining, tungsten alloy tubes have significant

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corrosion resistance and can withstand corrosive media such as acids, alkalis, and salts, thus extending the service life of wear-resistant liners .

### 3. Reduce maintenance frequency and downtime

Excellent wear resistance effectively reduces the replacement frequency of the liner , reduces equipment maintenance costs and downtime, and improves production efficiency.

### 3. Technical requirements for tungsten alloy tubes in industrial molds and wear-resistant liners: Dimensional accuracy and wall thickness uniformity .

Tungsten alloy tubes must have strict dimensional control and wall thickness uniformity to ensure the accuracy of mold assembly and uniform wear resistance of the liner .

#### 1. Surface quality and defect control

The surface of the pipe should be smooth and free of defects such as cracks and pores to avoid stress concentration leading to early damage. At the same time, the surface roughness must meet the bonding requirements of the wear-resistant layer or coating.

#### 2. Tungsten alloy tubes should have good machining properties and be easy to process into complex shapes of mold components and liner structures.

### 4. Typical Application Cases

- **for extrusion die core rods and bushings**

are used for core rods and bushings of high-strength extrusion dies to improve wear resistance and dimensional stability, ensuring continuous high-quality production of metal profiles.

- **Mining wear-resistant liner**

is used for the inner lining of mine conveying pipelines to withstand high-speed erosion of materials such as sand and gravel, extend the life of the pipeline and reduce maintenance frequency.

- **Plastic injection mold bushings**

improve the wear resistance of the core components of the injection mold, ensuring molding accuracy and mold service life.

### V. Future Development Trends

- **composite structure tungsten alloy tubes**

combines high toughness materials to develop composite tubes with different properties of inner and outer layers, taking into account both wear resistance and impact resistance.

- **Nano-strengthening and surface coating technology**

uses nanotechnology to strengthen the performance of the tungsten alloy tube matrix and cooperates with wear-resistant coating to improve the comprehensive wear resistance.

- **Intelligent monitoring and life prediction**

integrate sensor technology to achieve real-time monitoring and life prediction of the usage status of tungsten alloy tube molds and liners , improving maintenance efficiency.

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## VI. Summary

Tungsten alloy tubes, with their exceptional wear resistance, high strength, and high-temperature resistance, have become an irreplaceable structural support material for industrial molds and wear-resistant liners. With the continuous advancement of manufacturing technology, the performance and application areas of tungsten alloy tubes will continue to expand, providing a solid guarantee for the efficient and stable operation of industrial production.

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

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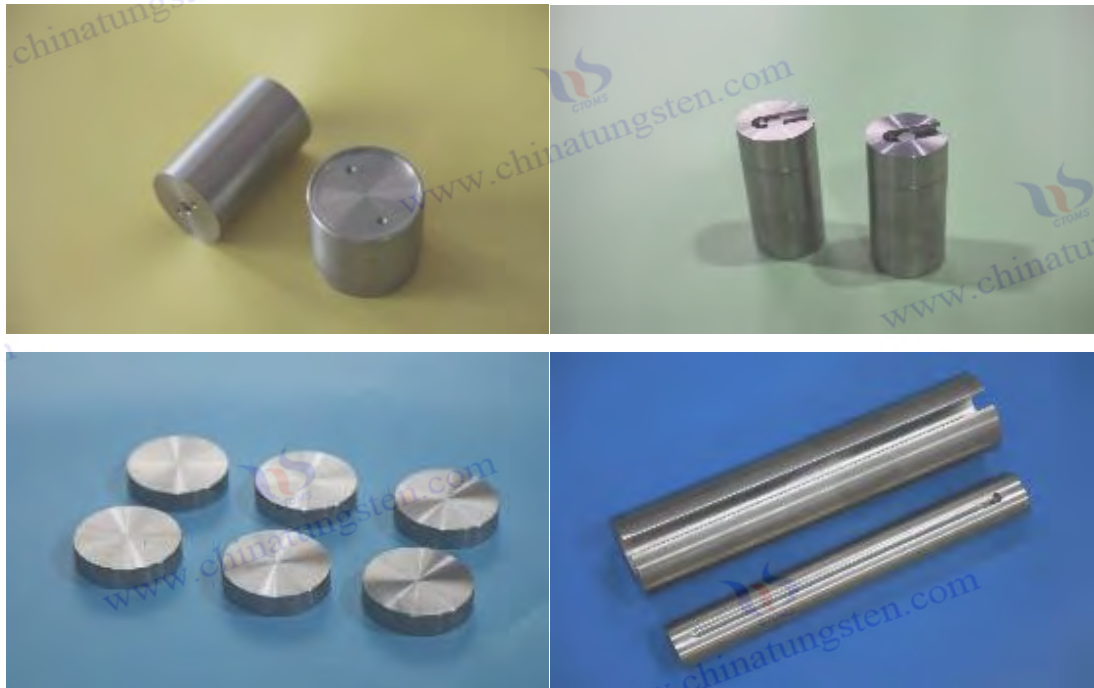
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电话/TEL: 0086 592 512 9696  
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[sales@chinatungsten.com](mailto:sales@chinatungsten.com)



## Chapter 6 Research and Development and Innovation Direction of Special Tungsten Alloy Tubes

### Preparation and Performance Optimization of Nanoparticle-Reinforced Tungsten Alloy Tubes

Nanoparticle-enhanced tungsten alloy tubes, a cutting-edge innovation in the tungsten alloy tube field, significantly enhance material properties by introducing nanoparticles into a traditional tungsten alloy matrix. This technology not only improves the mechanical properties of tungsten alloy tubes but also optimizes their wear resistance, thermal stability, and radiation resistance, providing strong material support for high-end applications.

#### Preparation technology of nanoparticle reinforced tungsten alloy tube

##### 1. Selection and Preparation of Nanoparticles:

Commonly used nanoparticles for reinforcement include oxides (e.g., zirconium oxide ( $\text{ZrO}_2$ ) and aluminum oxide ( $\text{Al}_2\text{O}_3$ ), carbides (e.g., titanium carbide ( $\text{TiC}$ ) and silicon carbide ( $\text{SiC}$ ), and metal nanoparticles (e.g., titanium and vanadium). These particles are prepared by chemical deposition, mechanical alloying, or sol-gel methods. Particle size is typically controlled within the 10-100 nm range to ensure good dispersion and reinforcement.

##### 2. Powder mixing and uniform dispersion:

Uniform mixing of nanoparticles with tungsten powder and binder metal powder is key to preparing high-performance nano-enhanced tungsten alloy tubes. Ball milling and ultrasonic dispersion techniques are used to improve the uniform distribution of nanoparticles in the metal matrix and avoid particle agglomeration and interface defects.

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3. **Powder metallurgy forming process optimization involves**  
compacting the mixed powder using molding techniques such as die pressing and isostatic pressing, followed by high-temperature sintering. Sintering parameters (temperature, atmosphere, and time) are optimized experimentally to promote good bonding between the nanoparticles and the matrix, while also controlling the densification process and reducing porosity and cracks.
4. **Heat treatment strengthens**  
the nano-enhanced tungsten alloy tube. Through heat treatment, the microstructure is regulated, the interface interaction between nanoparticles and the matrix is promoted, a strengthening phase is formed, and the comprehensive performance of the alloy is significantly improved.

## 2. Performance Advantages of Nanoparticle Reinforced Tungsten Alloy Tube

1. **Strengthening mechanical properties**  
Nanoparticles significantly improve the tensile strength, yield strength and fracture toughness of tungsten alloy tubes by hindering dislocation movement and grain boundary migration, effectively improving the defect of brittle fracture of traditional tungsten alloy tubes.
2. **Improve wear resistance and impact resistance**  
Nanoparticles have high hardness and are evenly distributed, which enhances the wear resistance of the matrix, effectively resists mechanical friction and impact loads, and is suitable for high wear conditions.
3. **Improve thermal stability and thermal conductivity**  
Nano-enhanced structures improve the stability of materials in high-temperature environments, reduce thermal expansion and thermal fatigue damage, while maintaining or improving good thermal conductivity to meet high-temperature service requirements.
4. **Nanoparticles with enhanced radiation resistance can capture and passivate defects caused by radiation, reduce the degradation of material properties caused by irradiation, and are suitable for high-radiation occasions such as the nuclear industry.**

## 3. Application Prospects of Nanoparticle Reinforced Tungsten Alloy Tubes

1. **Nano-enhanced tungsten alloy tubes for high-temperature aerospace structural parts**  
can be used as materials for key components such as high-temperature nozzles and combustion chamber liners, meeting the requirements of high temperature, high strength and corrosion resistance.
2. **Shielding and structural materials in the nuclear energy field**  
have excellent radiation resistance and high strength properties, making them suitable for internal structural parts and radiation protection shielding of nuclear reactors.
3. **High-performance armor-piercing projectile cores and protective components in military equipment**

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improve the strength and toughness of armor-piercing projectiles and enhance the wear resistance and impact resistance of protective armor.

4. **Wear-resistant bushings and supports in high-precision instruments**

increase the lifespan and performance stability of instrument components and reduce maintenance costs.

**4. Challenges and Future Research Directions in the Preparation of Nanoparticle-Reinforced Tungsten Alloy Tubes**

1. **The uniform dispersion control of nanoparticles**

to avoid particle agglomeration remains a key technical challenge in the preparation process, and more efficient dispersion technologies and composite methods need to be developed.

2. **The study of interface bonding mechanism**

provides a deeper understanding of the interaction between nanoparticles and tungsten matrix interfaces, which will help to design more stable and efficient reinforcement phase structures.

3. **The scale-up and cost control of the preparation process**

promote the industrial application of nano-enhancement technology, which requires solving the cost and efficiency issues of powder preparation, forming and heat treatment.

4. **The development of multifunctional nanocomposites**

combines multiple functions such as conductivity and anti-magnetism to meet the higher requirements of future high-end equipment for the comprehensive performance of materials.

**V. Summary**

nanoparticle-reinforced tungsten alloy tubes demonstrate significant potential for improving the mechanical strength, wear resistance, and thermal stability of conventional tungsten alloy tubes. With continued advancements in preparation technology and theoretical research, these materials will play an increasingly important role in aerospace, nuclear energy, military, and high-end manufacturing, driving technological innovation and industrial upgrading in tungsten alloy tube materials .

**Design Strategy and Microstructure Control of Microalloyed Tungsten Alloy Tubes**

Microalloyed tungsten alloy tubes are an advanced material technology that optimizes the microstructure and enhances performance by adding trace alloying elements to the traditional tungsten alloy tube matrix. Relying on precise element design and control, this technology effectively improves the mechanical properties, thermal stability, and corrosion resistance of tungsten alloy tubes, providing a solid material foundation for high-end applications.

**Design Strategy of Microalloyed Tungsten Alloy Tube**

1. Elements commonly used in microalloying include titanium (Ti), niobium (Nb), vanadium (V), aluminum (Al), zirconium (Zr), and small amounts of rare earth elements (such as lanthanum La and cerium Ce). These elements

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generally have high solid solution strengthening and precipitation strengthening effects, which can significantly affect the microstructure evolution and performance of the alloy.

2. **Optimizing Element Content and Ratios:**

The addition of microalloying elements is generally controlled between 0.1% and 1.0%, which maximizes the strengthening effect while avoiding embrittlement or manufacturing complexity caused by excessive amounts. By calculating thermodynamic equilibrium and experimental feedback, the ratio of each element is adjusted to achieve the optimal balance between strengthening and toughness.

3. **Synergistic strengthening mechanism design**

makes full use of the multiple strengthening mechanisms of microalloying elements, such as solid solution strengthening, grain refinement and precipitation of second phase, to form fine and uniform precipitates and improve the comprehensive performance of the alloy.

4. **Process adaptability considerations**

Microalloy design must take into account the adaptability of forming, sintering and heat treatment processes to ensure that alloy elements do not undergo adverse phase changes or agglomeration during the preparation process and maintain uniform and stable structure.

## 2. Microstructure Control Method of Microalloyed Tungsten Alloy Tube

1. **Microalloying**

elements form fine precipitates that hinder grain boundary migration, promote grain refinement, and enhance the material's strength and toughness. Furthermore, uniform microstructure distribution is achieved by controlling sintering and heat treatment temperature and time.

2. **Control of the morphology and distribution of the precipitated phase**

regulates the morphology (such as carbides, nitrides or oxides) and distribution uniformity of the precipitated phase, prevents the aggregation of coarse precipitates, and reduces the weak interface and defect sources of the material.

3. **Interface strengthening mechanism:**

Microalloying elements can form a strong bond at the interface between the matrix and the precipitated phase, thereby improving the interfacial bonding strength and enhancing the material's fracture resistance.

4. **Heat treatment process adjustment**

: Rationally design annealing, solution and aging processes to promote the effective solution and precipitation of micro-alloying elements and adjust the hardness and plasticity of the material.

## Performance Improvement of Microalloyed Tungsten Alloy Tube

1. **Improved Mechanical Properties**

Microalloying significantly improves tensile strength and yield strength while maintaining good ductility and fracture toughness, solving the brittle defect of traditional tungsten alloys.

2. **Enhanced thermal stability,**

refined grains and uniform precipitated phase structure improve the organizational stability

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of tungsten alloy tubes in high temperature environments, reduce thermal expansion coefficient, and reduce thermal fatigue damage.

3. **Improved wear and corrosion resistance:**

The hard second phase and stable protective oxide film formed by micro-alloying elements enhance the wear and corrosion resistance of the material surface and extend its service life.

4. **Process performance optimization**

After microalloying, the densification effect of tungsten alloy tubes is improved, the processing performance is improved, the crack and defect generation rate is reduced, and it can adapt to more complex forming and processing requirements.

## Application Prospects of Microalloyed Tungsten Alloy Tubes

1. **tungsten alloy tubes in high-end equipment manufacturing**

, aerospace, nuclear industry and military fields is growing, and microalloying technology can meet the requirements of harsh service environments.

2. **High-temperature reactor components and heat exchanger linings under high-temperature extreme conditions require**

tungsten alloy tubes with excellent thermal stability and corrosion resistance. Microalloying provides an effective material solution.

3. **Precision Machinery and Molds**

Micro-alloyed tungsten alloy tubes are widely used in precision machinery manufacturing, especially in wear-resistant and impact-resistant structural parts.

## V. Future Development Directions and Challenges

1. **Multi-element microalloying collaborative design**

further develops multi-element composite microalloying design, explores the synergistic strengthening effect of different elements, and promotes breakthroughs in material performance.

2. **Real-time microstructure monitoring technology**

is combined with advanced characterization methods, such as transmission electron microscopy (TEM) and synchrotron radiation X-rays, to achieve dynamic evolution monitoring of microalloying elements and precipitated phases, and guide process optimization.

3. **The process integration optimization**

integrates the entire process of powder preparation, forming, sintering and heat treatment to improve the preparation efficiency and consistency of micro-alloyed tungsten alloy tubes.

4. **Considering**

**environmental protection and economy**, we develop green and energy-saving microalloying processes, reduce production costs, and promote the transformation of technology to large-scale industrial applications.

## Summarize

Microalloying technology significantly improves the overall performance of tungsten alloy tubes

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through precise design and effective control of trace elements in them. As an important approach to improving the performance of tungsten alloy tubes and expanding their application areas, the research and development of microalloyed tungsten alloy tubes will become a key direction for the future development of high-performance tungsten-based materials .

### **Electrical, thermal and anti-magnetic properties of multifunctional tungsten alloy tubes**

Multifunctional tungsten alloy tubes are advanced materials that combine high strength, high density, and specialized functions, particularly outstanding in electrical and thermal conductivity, as well as anti-magnetic properties. With the increasing demand for high-end equipment manufacturing and extreme operating conditions, the development of tungsten alloy tubes with composite functions has become a cutting-edge direction in materials science. The following details the combined electrical, thermal, and anti-magnetic properties of multifunctional tungsten alloy tubes, their influencing factors, preparation techniques, and application advantages.

## **1. Conductive Properties of Multifunctional Tungsten Alloy Tube**

### **1. Conductivity Mechanism and Influencing Factors:**

The conductivity of tungsten alloy tubes is primarily influenced by alloy composition, microstructure, and impurity content. Tungsten inherently has high electrical conductivity. While adding binder metals such as nickel and iron can improve mechanical properties, it also reduces overall conductivity. By manipulating the alloying element ratio and optimizing the microstructure, electrical conductivity can be enhanced while maintaining mechanical strength.

### **2. Highly conductive tungsten alloy tubes are designed**

using low-impurity, high-purity tungsten powder as the base material. The nickel-iron content is rationally controlled to promote grain refinement and uniform distribution, which helps reduce electron scattering and improve conductivity. Furthermore, the introduction of microalloying elements and nanoparticle reinforcement optimizes the electron transmission path and achieves high conductivity.

### **3. The influence of preparation process on conductivity**

The control of sintering temperature and atmosphere, and the optimization of heat treatment process can help reduce interface defects and pores, improve the electron flow channel, and thus improve the conductivity.

## **2. Thermal conductivity of multifunctional tungsten alloy tube**

### **1. Thermal conductivity:**

Tungsten alloy tubes primarily rely on free electrons and lattice vibrations to transfer energy. High-purity tungsten and optimized alloy design help reduce grain boundary scattering and defect scattering, thereby improving thermal conductivity.

### **2. Key factors influencing thermal conductivity**

include the alloy's binder metal content, microstructural density, grain size, and interfacial bonding quality. Nano-strengthening and micro-alloying techniques can effectively enhance thermal conductivity.

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3. **Process optimization for thermal conductivity:**

High-temperature sintering and heat treatment can improve material density and grain connectivity, reducing thermal resistance. Surface treatments (such as PVD coatings) can also help improve surface heat conduction efficiency.

3. **Antimagnetic properties of multifunctional tungsten alloy tube**

1. Tungsten and its alloys generally exhibit good diamagnetic **properties**

, making them suitable for applications requiring low magnetic interference. Alloy design modulates the material's magnetic response by controlling the content and distribution of magnetic elements such as iron and nickel.

2. **The anti-magnetic enhancement strategy**

optimizes the ratio of alloying elements, reduces the content of soft magnetic phases , and uses microalloying to form non-magnetic phases and interface structures to suppress magnetization. In addition, heat treatment processes can adjust the magnetic domain structure and improve anti-magnetic properties.

3. **Application significance of antimagnetic properties**

High antimagnetic tungsten alloy tubes are widely used in nuclear energy equipment, aerospace electronic shielding, high-precision instrument antimagnetic components and other fields to ensure stable operation of equipment and signal integrity.

4. **Composite Performance Control and Preparation Technology of Multifunctional Tungsten Alloy Tube**

1. **Composite performance collaborative design**

achieves an optimal balance among electrical conductivity, thermal conductivity, and anti-magnetic properties through precise design of material components, avoiding the negative impact of optimizing a single property on other properties. Multi-scale structural design and functional gradient technology are key tools.

2. **Advanced preparation technology**

uses advanced processes such as powder metallurgy, hot isostatic pressing, additive manufacturing , etc., combined with heat treatment and surface modification to achieve the preparation of high-density, multifunctional composite tungsten alloy tubes.

3. **Nano-reinforcement and interface engineering**

Nano-particle reinforcement and interface control technologies effectively enhance the synergistic performance of thermal, electrical and magnetic properties, and improve the overall performance and application adaptability of materials.

5. **Application Prospects of Multifunctional Tungsten Alloy Tubes**

1. **high-end electronic and communication equipment**

for electronic packaging, heat sinks and anti-interference shielding to improve equipment performance and reliability.

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## 2. Nuclear Industry and Medical Equipment

In nuclear reactors and radiotherapy devices, the composite properties of tungsten alloy tubes ensure shielding efficiency and equipment stability.

## 3. High-performance tungsten alloy tubes in the aerospace and defense fields

meet the structural and functional requirements of extreme environments, such as inertial navigation components, flow tubes and high-temperature protective sleeves.

## VI. Summary

Multifunctional tungsten alloy tubes combine excellent electrical and thermal conductivity with anti-magnetic properties, making them a crucial material for complex working conditions and high-end applications. Through the integration of alloy design, microstructure control, and advanced fabrication techniques, tungsten alloy tubes are continuously achieving breakthroughs in composite performance, providing a solid material foundation for the future development of intelligent manufacturing and high-performance equipment.

### 6.4 Thermal Stability of High- Tungsten Alloy Tubes and Heat Treatment Paths

High-temperature tungsten alloy tubes are widely used in aerospace, nuclear, and other high-temperature industries due to their excellent high-temperature mechanical properties and stable physical and chemical characteristics. The key to achieving the excellent performance of tungsten alloy tubes in high-temperature environments lies in the thermal stability of their microstructure and the design of appropriate heat treatment processes. This section explores the mechanism of microstructural thermal stability of high-temperature tungsten alloy tubes, the factors influencing it, and common heat treatment paths, providing scientific guidance for improving the material's comprehensive performance under high-temperature conditions.

#### 1. The connotation and significance of thermal stability of high temperature tungsten alloy tube

##### 1. Definition of Tissue Thermal Stability

Tissue thermal stability refers to the ability of a material to maintain its microstructure (grain size, phase structure, precipitate distribution, etc.) stable and not undergo adverse changes (such as grain coarsening, phase transformation, precipitate dissolution, etc.) in a high temperature environment.

##### 2. Influence of Thermal Stability on Performance

Good thermal stability ensures that the tungsten alloy tube maintains high strength, hardness and creep resistance when working at high temperatures, avoiding significant decline in material properties due to structural degradation.

##### 3. High temperature applications such as

aviation engine turbine blade casings, high temperature furnace linings, and nuclear reactor components all require tungsten alloy tubes to withstand high temperatures for a long time.

#### 2. Factors affecting thermal stability of high temperature tungsten alloy tube

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1. **in tungsten**

alloys form stable second-phase particles, inhibiting grain growth and dislocation movement, thereby improving thermal stability.

2. The fine and uniform grains and evenly distributed second phase particles **in the initial microstructural state are the basis for improving high-temperature stability.**

3. **Impurity Elements and Inclusions**

Impurities and inclusions will become the first sites for grain coarsening and reduce thermal stability.

4. **Heat treatment history**

The heat treatment process directly affects the formation and distribution of precipitated phases and regulates the structural stability of the alloy.

**3. Typical organizational evolution of high temperature tungsten alloy tubes**

1. **grains**

tend to grow, resulting in reduced plasticity and strength. The pinning effect of the second phase particles can effectively inhibit grain coarsening.

2. **Precipitation and dissolution of precipitated phases**

High temperatures may cause the dissolution or re-precipitation of strengthening phases, affecting mechanical properties.

3. **Phase transformation behavior**

Some alloys may undergo high-temperature phase transformation, and heat treatment is required to control the phase stability.

**4. Heat Treatment Path Design of High-Temperature Tungsten Alloy Tube**

1. **Solution treatment**

promotes uniform dissolution of alloy elements, eliminates internal stress, and improves plasticity and uniformity through high-temperature solution treatment.

2. **Aging treatment**

is carried out at an appropriate temperature to promote the uniform precipitation of strengthening phases and improve high temperature strength and thermal stability.

3. **The multi-stage heat treatment process**

combines solid solution and multi-stage aging to optimize the size and distribution of the strengthening phase and maximize the overall performance.

4. **Annealing treatment**

is carried out under controlled temperature and time conditions to improve toughness, restore structure and adapt to different application requirements.

**5. Optimization of high temperature heat treatment process parameters**

1. **The temperature-controlled**

solution temperature is generally selected above the dissolution temperature of the

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strengthening phase, and the aging temperature needs to be determined in combination with the precipitation temperature of the strengthening phase.

2. **The holding time**

ensures sufficient and uniform solid solution and aging reaction to avoid excessive coarsening.

3. **cooling**

or controlled cooling affects the morphology and distribution of the precipitated phase and needs to be optimized according to performance requirements.

## 6. Maintenance of tissue stability in high-temperature service environment

1. **Thermal Cycle Stability**

High-temperature tungsten alloy tubes are prone to structural degradation during repeated thermal cycles, and require a combination of heat treatment and alloy design to improve cycle life.

2. **High-temperature oxidation and corrosion**

The formation of surface oxide film and the application of corrosion-resistant coatings are key measures to ensure high-temperature stability.

3. **Stress relaxation and creep**

can enhance creep resistance and extend service life through reasonable organizational regulation and heat treatment.

## VII. Examples and Research Progress

1. **Advanced tungsten alloy tube heat treatment case introduces the typical**

solution + aging heat treatment process of high-temperature tungsten alloy tube and its influence on the microstructure and performance.

2. **Nanoparticle Enhancement and High-Temperature Stability**

The latest research results on nanoparticle enhancement technology to improve thermal stability.

3. **Heat treatment process simulation and optimization**

Based on computational materials science, heat treatment parameter simulation is used to achieve process optimization.

## 8. Summary and Outlook

high-temperature tungsten alloy tubes is the core guarantee of their high-temperature performance. By scientifically designing alloy composition, optimizing heat treatment paths, and combining advanced nano-strengthening technology and surface protection measures, the performance of tungsten alloy tubes under extreme high-temperature conditions can be significantly improved. In the future, combined with intelligent manufacturing and material simulation technologies, the heat treatment process for tungsten alloy tubes will become even more precise and efficient, providing more reliable key material solutions for the aerospace, nuclear energy, and high-temperature industries.

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## 6.5 Study on the interface bonding mechanism of tungsten-copper/tungsten-nickel composite tungsten alloy tube

As advanced equipment places greater demands on multifunctional material properties, single-component tungsten alloy tubes are increasingly unable to meet the comprehensive performance requirements of high density, high thermal conductivity, high strength, and good machinability. Composite tungsten alloy tubes, particularly those composed of tungsten-copper (W-Cu) and tungsten-nickel (W-Ni) composite structures, are becoming an important material choice for high-end applications (such as nuclear power plants, particle accelerator components, and thermal control systems) due to the synergistic performance benefits of multiphase integration. This section systematically explores the interfacial bonding mechanisms of tungsten-copper/tungsten-nickel composite tungsten alloy tubes, including the physical, chemical, and metallurgical bonding processes and their impact on the final performance. This provides a theoretical basis and technical support for optimizing the preparation of composite materials.

### 1. Structural Characteristics and Application Background of Tungsten-Copper/Tungsten-Nickel Composite Tungsten Alloy Tube

#### 1. Tungsten-copper composite tungsten alloy tubes

combine the high melting point and high strength of tungsten with the excellent electrical and thermal conductivity of copper. They are widely used in high heat flux density components (such as electrodes, heat sinks, and plasma collision device sleeves).

#### 2. Features of Tungsten-Nickel Composite Tungsten Alloy Tube: Tungsten-nickel alloys are commonly used in inertial components, protective components, and high-impact areas due to their excellent workability and toughness. Their composite design can improve service reliability.

#### 3. The trend of multifunctional composite structure

Composite pipes adopt multi-layer design (such as tungsten copper inner layer and tungsten nickel outer layer), which takes into account strength, thermal conductivity and corrosion resistance, and has become the forefront of aviation, nuclear energy and military material research.

### 2. Interface connection types of tungsten copper/tungsten nickel composite tungsten alloy tubes

#### 1. Physical mechanical bonding

mainly relies on surface roughness, compression force and interface contact area. It is a non-metallurgical connection with limited bonding strength.

#### 2. Diffusion bonding (metallurgical bonding)

promotes the diffusion of tungsten and Cu/Ni atoms at the interface through high-temperature heat treatment, forming a diffusion layer or intermediate phase, which is a more ideal bonding form.

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3. **The reaction bonding/intermediate phase formation**  
system may form characteristic intermediate compounds at the interface, such as W-Ni alloy zone and W-Cu transition layer, which enhance the interface strength.
4. **Liquid phase infiltration/cladding sintering**  
utilizes liquid copper or nickel to infiltrate into the porous tungsten skeleton at high temperature to form an interface metallurgical bond, which is commonly used in the manufacture of composite formed tungsten alloy tubes.

### 3. Analysis of the bonding mechanism of tungsten-copper interface

1. **The solid-liquid infiltration combination utilizes the low melting point of copper and**  
realizes the tungsten-copper bonding through the capillary penetration of liquid copper into the pre-sintered tungsten tube blank.
2. **Interface diffusion layer**  
Although tungsten and copper are immiscible, an interface transition layer of tens of nanometers will still be formed at high temperatures to enhance the bonding strength.
3. **Interface crack control**  
Due to the large difference in thermal expansion coefficients between the two, controlling the cooling rate and introducing a gradient layer structure are the keys to preventing thermal cracks.

### 4. Analysis of the bonding mechanism of tungsten-nickel interface

1. **Solid-state diffusion and eutectic reaction There is a certain solid solubility**  
between tungsten and nickel, which can diffuse and bond during high-temperature sintering to form a W-Ni solid solution.
2. **Intermetallic phases**  
such as  $\text{Ni}_4\text{W}$  and  $\text{NiW}$  formed at high temperatures enhance the interfacial bonding strength, but excessive formation will lead to increased brittleness.
3. **Strengthening mechanism:**  
W particles are dispersed in the Ni matrix to form a typical dual-phase structure, which can prevent crack propagation and improve impact toughness.

### 5. Characterization of the Interface Microstructure of Composite Tungsten Alloy Tube

1. **Scanning electron microscopy (SEM) observation**  
was used to observe the interface micromorphology, crack source, pore distribution and element diffusion zone width.
2. **Energy dispersive spectroscopy (EDS)**  
analyzes the element concentration gradient at the W-Cu or W-Ni interface to evaluate the diffusion layer thickness and composition uniformity.
3. **Transmission electron microscopy (TEM) and XRD**  
can reveal the formation of new phases, dislocation structure and possible existence of nano-precipitates at the interface.

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6. Interface bonding performance evaluation and optimization technology

- Shear strength and peel strength tests**  
are used to quantitatively evaluate the interface bonding strength of composite pipes and are key testing methods before industrial application.
- Thermal fatigue testing**  
simulates the interface stability of composite pipes during thermal cycles and reflects their adaptability to the service environment.
- The interface stress control design**  
adjusts the thermal expansion mismatch through an intermediate buffer layer (such as the W-Ni-Cu gradient structure) to improve reliability.
- New joining technologies**  
such as laser welding, hot isostatic pressing, and reaction diffusion joining have shown great potential in terms of interface strength and integrity.

7. Typical Composite Tungsten Alloy Tube Case Analysis

type	Inner material	Outer material	Connection method	Application Scenario
W-Cu-W tube	copper	Tungsten	Liquid phase infiltration	High frequency induction heating tube
W-Ni-W tube	nickel	Tungsten	Hot pressing diffusion bonding	Tactical Inertial Flight Kit
W-Ni-Cu tube	Ni-Cu alloy	Tungsten	Powder co-sintering	Particle beam injection system pipe wall

8. Future Development Directions and Challenges

- Multilayer gradient structure composite design**  
adopts transition layer or functionally gradient material (FGM) design concept to alleviate thermal stress and interface mismatch problems.
- Research on interface strengthening coatings**  
explores interface modification methods such as nanolayer coatings and electroplated alloy layers to enhance bonding performance and corrosion resistance.
- Intelligent interface monitoring and life prediction**  
combines acoustic emission, ultrasound, XCT and other technologies to achieve online detection of interface damage and life assessment during service.
- Green process development**  
promotes the application of new connection technologies with low energy consumption and high bonding efficiency in the manufacturing of composite tungsten alloy tubes.

Summarizing the interfacial bonding mechanism of

tungsten-copper/tungsten-nickel composite tungsten alloy tubes is key to achieving synergistic composite structural performance. By deeply understanding the physical and chemical bonding



processes, optimizing heat treatment pathways, and controlling interfacial microstructures, high-performance composite tungsten alloy tubes will play an even more important role in extreme operating conditions and multifunctional integrated scenarios.

## Surface Coating and Corrosion Resistance Enhancement Technology of Functionalized Tungsten Alloy Tubes

With the widespread application of tungsten alloy tubes in high-end fields such as nuclear energy, aerospace, medical treatment, and electronics, their service environments are becoming increasingly complex, often facing extreme challenges such as high temperatures, severe corrosion, high radiation, and strong oxidation. To improve the surface corrosion resistance, wear resistance, thermal stability, and functionalization level of tungsten alloy tubes, surface coating technology has become a key means to enhance their service performance. This section systematically explains the coating types, preparation processes, performance optimization mechanisms, and technical approaches for improving corrosion resistance of tungsten alloy tube surfaces.

### 1. Overview of tungsten alloy tube surface corrosion problems

Although tungsten alloy itself has certain chemical stability and high temperature oxidation resistance, there is still a risk of surface failure in the following environments:

- **High temperature oxidizing environment** : At 600–1000°C, tungsten easily forms brittle  $WO_3$  oxide , which then peels off;
- **Acidic/alkaline corrosive media** : exhibits obvious corrosive reaction in strong acid, strong alkali or fluoride solution;
- **Electrolyte or physiological environment** : Medical equipment or marine environment may face electrochemical corrosion and localized pitting corrosion;
- **Friction corrosion and abrasive corrosion** : Under high-frequency vibration and particle contact, a fatigue peeling layer is easily formed on the surface.

### 2. The main function of functional surface coating

1. **Improve corrosion resistance** : prevent direct contact between corrosive media and base metal;
2. **Improve wear and impact resistance** : Hard coating can significantly reduce surface wear;
3. **Enhanced thermal stability and antioxidant capacity** : Oxide coating can form a dense protective film;
4. **Realize surface functionalization** : such as electrical conductivity, thermal conductivity, anti-reflection, electromagnetic shielding and other properties;
5. **Improve surface finish and interface bonding** : facilitate subsequent packaging, welding, connection and other processing.

### 3. Common Surface Coating Types and Technologies of Tungsten Alloy Tubes

#### 1. Electroless Plating

- Common coatings: Ni-P, Ni-B, Ni-Cr, etc.

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- Advantages: The coating has good uniformity, can cover the inner wall, and is suitable for complex pipelines.
- Application: Improve corrosion resistance and electromagnetic compatibility.

## 2. Physical Vapor Deposition (PVD)

- Coating types: TiN , CrN , ZrN , AlTiN , MoS<sub>2</sub> , etc.
- Features: dense coating, strong adhesion, and thickness can be controlled at the nano level .
- Applications: high temperature structures, wear-resistant components, radiation protection coatings, etc.

## 3. Chemical Vapor Deposition (CVD)

- Coating type: SiC , TiC , Cr<sub>3</sub>C<sub>2</sub> , WC and other ceramic coatings .
- Advantages: The coating has extremely high hardness and is suitable for extreme corrosive environments.
- Disadvantages: The deposition temperature is high and the thermal stability of the substrate is required to be high.

## 4. Thermal Spray Technology (Plasma/Flame Spray)

- Commonly used materials : Al<sub>2</sub>O<sub>3</sub> , Cr<sub>2</sub>O<sub>3</sub> , NiCr , WC- Co , etc.
- Advantages: Suitable for large-area exterior wall treatment and can form thick composite coatings.
- Applicable scenarios: aviation thermal control components, high radiation area sheaths, etc.

## 5. Sol-Gel Coating

- Features: low cost, suitable for complex shape structures.
- Application: Multifunctional thin film coatings (conductive/antibacterial/hydrophobic) have great development potential.

## 6. Electrochemical coating (anodizing, electroplating)

- Can achieve nickel, copper, metal oxide coverage, etc.
- tungsten alloy tubes in the conductive or medical fields .

## 4. Coating Adhesion and Interface Optimization Technology

1. **Interface cleaning and pretreatment** : such as sandblasting, pickling, and plasma cleaning to improve bonding activity;
2. **Introduction of transition layer** : Ni intermediate layer and Cr bonding layer are set to alleviate thermal expansion mismatch;
3. **Multi-layer composite structure design** : such as hard layer + tough layer combination , gradient layer structure, etc.
4. **Sintering/densification after heat treatment** : enhance metallurgical bonding of coating and reduce porosity;
5. **Surface roughening treatment** : Improve coating adhesion through etching, laser drilling and other methods.

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5. Tungsten Alloy Tube Coating Performance Test and Corrosion Evaluation Method

Performance indicators	Detection method
coating thickness	SEM cross-section analysis, XRF thickness meter
Adhesion	Tensile peel test, scratch test
Corrosion resistance	Salt spray test, acid immersion test, Tafel curve
hardness	Vickers hardness, nanoindentation
Wear resistance	Ball-disc friction test, fatigue wear test

6. Typical Application Cases of Tungsten Alloy Tube Coating Technology

Application Scenario	Coating solutions	Main Function
Nuclear reactor cooling pipes	Cr <sub>2</sub> O <sub>3</sub> - PVD ceramic layer	Improve corrosion resistance and radiation stability
Medical radiotherapy device sleeve	Ni-P chemical plating	Improve acid and alkali resistance and biological stability
Heat pipe assembly	AlTiN coating	Improve surface hardness and thermal conductivity
Laser cooling system	WC-Co spray coating	Enhanced wear resistance and thermal shock resistance

VII. Future Development Directions and Research Hotspots

- of intelligent responsive coatings**  
Responsive intelligent coatings that automatically adjust surface properties under specific environments such as high temperature/strong acid.
- Superhydrophobic/anti-scaling functionalized coating**  
solves the scaling problem of tungsten alloy tubes in cooling water or physiological fluids.
- The in-situ self-healing coating system**  
extends the coating service life and improves multi-cycle service stability.
- Green and environmentally friendly low-temperature coating technologies**  
such as room temperature plasma coating technology and low-temperature CVD methods.

Conclusion:

Functional coating technology for tungsten alloy tubes is a key component in the future development of high-performance and multifunctional integration. Through material selection, structural design, preparation process optimization, and interface control, tungsten alloy tubes can demonstrate excellent comprehensive performance in more demanding service environments, promoting their widespread application and upgrading in high-end manufacturing fields.

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## Chapter 7 International Standards and Compliance System for Tungsten Alloy Tubes

### 7.1 Chinese National/Industry Standards for Tungsten Alloy Tubes (GB/T, YS/T)

In China, tungsten alloy tubes, as a high-performance metal material, are widely used in strategic industries such as nuclear energy, aerospace, military, medical, and electronics. Their production, inspection, and use are regulated by multiple national and industry standards. China's current standards system is primarily based on national standards (GB/GBT) and industry standards (YS/T, for the metallurgical industry), covering raw materials, physical properties, chemical composition, test methods, dimensional tolerances, and safe packaging.

#### 1. Application of Chinese National Standards (GB, GB/T) in Tungsten Alloy Tubes

China's national standards (GB) and recommended national standards (GB/T) are important components of the national quality supervision system, ensuring the universality, safety, and interchangeability of tungsten alloy tube products in the domestic market. Although there is currently no independent national standard specifically for "tungsten alloy tubes", several relevant standards can be used as references:

- **GB/T 4187.1-2008 "General Rules for Chemical Analysis of Tungsten and Tungsten Products"**  
→ specifies the general requirements for chemical composition analysis of tungsten-based materials (including tungsten alloys);
- **GB/T 34920-2017 "High-density tungsten alloy rods"**  
→ This standard applies to deformation processing materials for high-density tungsten alloys such as tungsten -nickel-iron and tungsten-nickel-copper. Some of its technical requirements can be used as a reference for pipe design.

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- **GB/T 25744-2010 "Tungsten-based Heavy Alloy Compacted and Sintered Blanks"**  
→ Standardizes the physical properties, compositional deviation, and appearance quality requirements for powder metallurgy tungsten alloy compacts;
- **GB/T 15825-1995 "Determination of density of powder metallurgy metal structural parts"**  
→ Standardized method for density testing of tungsten alloy tubes;
- **GB/T 2423 series, GB/T 10125-2021**  
→ Related to environmental adaptability testing standards such as corrosion resistance, thermal cycling, and salt spray testing.

## 2. Some specifications of China Metallurgical Industry Standard (YS/T) applicable to tungsten alloy tubes

YS/T standard is a metallurgical industry standard issued by China Nonferrous Metals Industry Association and its subordinate organizations. The following are closely related to tungsten alloy pipes:

- **YS/T 798-2012 "Powder Metallurgy Heavy Tungsten Alloys"**  
→ This standard specifies the composition, density, mechanical properties, and dimensional control standards for tungsten-based alloys (such as tungsten-nickel-iron and tungsten-nickel-copper). Part of this standard applies to the performance evaluation of tungsten alloy tube blanks or finished products.
- **YS/T 1083-2015 "General Rules for Packaging, Marking, Storage and Transportation of Tungsten and Tungsten Alloy Products"**  
→ This standard specifies the technical requirements for packaging, protection and transportation of tungsten materials and serves as an important basis for tungsten alloy tube packaging regulations.
- **YS/T 1187-2017 "Technical Specification for Hot-Worked Products of High-Gravity Tungsten Alloys"**  
→ Applicable to tungsten alloy structural parts formed by hot rolling, forging, and extrusion. Although it does not directly cover pipes, it provides an important reference for wall thickness control and mechanical property evaluation;
- **YS/T 1190-2017 Technical Specifications for Sintered Tungsten and Tungsten Alloy Products**  
→ Applicable to the determination of dimensional accuracy and defect control of sintered tube blanks or near-net-shape tungsten tubes .

## 3. Scope of application of the standard and quality grade classification

Most tungsten alloy tube manufacturers will formulate enterprise standards or internal control specifications based on the general requirements of the above standards and their own product characteristics. Common quality grade classifications of materials in the standards include:

- **Density grade ( $\geq 17.0, 17.5, 18.0, 18.5, 18.8 \text{ g/cm}^3$ ) ;**
- **Mechanical property grade (divided by tensile strength and elongation) ;**

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- **Surface grade (processed, polished, bright) ;**
- **Dimension tolerance grade (commonly  $\pm 0.05\text{mm} \sim \pm 0.2\text{mm}$ ) .**

#### IV. Connection with international standards and certification

In recent years, with the expansion of tungsten alloy tube exports, domestic companies have gradually aligned Chinese standards with international standards (ASTM, MIL, ISO, etc.). Common approaches include:

- List the implementation standards in the product description, such as "Implementation standards: YS/T 798-2012, reference ASTM B777-15";
- Provide bilingual inspection reports and certificates in Chinese and English to meet overseas quality traceability requirements;
- Implement standard equivalence conversion and certification registration, such as ISO 9001 quality management system, RoHS/REACH compliance declaration, etc.

#### V. Conclusion

China has yet to establish a complete, independent standards system for tungsten alloy tubes, a series of existing national and industry standards provide a crucial foundation for ensuring manufacturing quality, testing technology, and product consistency. In the future, as tungsten alloy tubes penetrate and develop in high-end fields like aviation, nuclear energy, and electronics, they are expected to further refine and internationalize specialized standards, boosting China's technological leadership and market share in the global tungsten alloy industry.

### 7.2 Interpretation of the American Standard System (ASTM, MIL) for Tungsten Alloy Tubes

Tungsten Heavy Alloy Tubes (Tungsten Heavy Alloy Tubes) are widely used in the United States in the nuclear industry, aerospace, military, medical protection, and high-temperature structural components. Due to their high density, high strength, and excellent heat and radiation resistance, the US material standards system imposes extremely stringent quality requirements on tungsten alloy tubes. The US primarily uses the ASTM (American Society for Testing and Materials) and MIL (Military Standard) systems to regulate tungsten alloy tubes and related products. This section will detail the core standards, technical specifications, and application integration of tungsten alloy tubes under these two systems.

#### 1. Specifications related to tungsten alloy tubes in ASTM standards

ASTM (American Society for Testing and Materials) is one of the world's most authoritative materials standards organizations, and its published standards are widely adopted and implemented worldwide. Although ASTM has not developed a separate standard for "tungsten alloy tubes," several high-density tungsten alloy and tungsten product standards can provide a reference for the production and inspection of tungsten alloy tubes:

#### 1. ASTM B777-15 Standard Specification for Pressed and Sintered Heavy Tungsten Metal Alloy Products

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- **Scope of application** : Covering pressed and sintered products of high-density alloys such as tungsten-nickel-iron and tungsten-nickel-copper, suitable for pipe blanks or near-net-shape parts.
- **Performance level** : Class 1–4, corresponding to different densities (17.0–18.5 g/cm<sup>3</sup>) and mechanical properties.
- **Tube suitability** : It can be used as the basic material specification for tungsten alloy tubes, providing composition range, density control and mechanical property targets.

**2. ASTM B705 "General Specification for Tungsten and Tungsten Alloy Tubing" (Note: Although it refers to tungsten tubes rather than tungsten alloys, it is still of reference value)**

- **Regulations** : pipe size deviation, wall thickness control, surface quality, curvature and test methods.
- **Applicable materials** : pure tungsten and its alloy hot-processed pipes, cold-rolled or annealed products.

**3. ASTM E8/E8M - Tensile Test Methods for Metallic Materials**

- **Application** : Used for mechanical property testing of tungsten alloy tubes, including tensile strength, yield strength and elongation evaluation.
- **Supporting tests** : Often used in conjunction with ASTM B777 to ensure that the product meets the end-use strength requirements.

**4. ASTM E384 - Microhardness Test Method**

- **Used to evaluate** : Vickers/ Knoop hardness of the inner and outer wall surfaces of tungsten alloy tubes , especially suitable for high-density products.

**5. ASTM E112 - Grain Size Evaluation Method**

- **Structure control** : used to detect the microstructure uniformity of tungsten alloy tubes after sintering or heat treatment.

**2. Application Scenarios of Tungsten Alloy Tubes in MIL Military Standards**

US military standards (MIL-SPEC / MIL-STD) are primarily used for the selection and acceptance of key materials in military equipment and systems. Tungsten alloy, due to its exceptional high specific gravity and kinetic energy performance, is widely used in missile cores, tail compartment counterweights , ballistic armor, and inertial system components. The following MIL standards are closely related to tungsten alloy tube manufacturing:

**1. MIL-T-21014C (Tungsten Base Alloy, High-Density)**

- **Applicable categories** : Covering high-density alloys based on tungsten (mainly W-Ni-Fe), including bars, forgings and pipes;
- **Typical applications** : Suitable for military structural parts such as high-strength anti-penetration parts (bullet cores), inertial components, etc.
- **Regulations** : including chemical composition, heat treatment conditions, density, tolerance, mechanical properties and appearance quality requirements;
- **Quality inspection** : including non-destructive testing (ultrasound, X-ray), metallographic analysis and hardness measurement, etc.

**2. MIL-STD-2154 (ultrasonic testing standard)**

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- **Application** : Used for internal defect detection of military parts such as tungsten alloy tubes;
- **Grading** : Acceptability is determined based on defect size and reflection amplitude.

### 3. MIL-STD-883 (Environmental testing for microelectronic devices)

- **Reference value** : If tungsten alloy tubes are used in electronic packaging or heat sink structures, their thermal shock resistance, electrical insulation and sealing properties can refer to this standard test specification.

### 3. Technical Characteristics and Advantages of the U.S. Standards System

Project Category	Characteristics of the standard system
<b>Standards</b>	ASTM and MIL standards are highly unified in terms of material composition, performance indicators, testing methods, etc., which facilitates global procurement and docking.
<b>Conformance</b>	
<b>Wide applicability</b>	Most ASTM standards are applicable to tungsten alloy plates, rods, tubes, and special-shaped parts, with high compatibility.
<b>Clear quality grading</b>	For example, B777 divides tungsten alloys into different "Classes" corresponding to specific density and strength levels, making it easier for companies to connect with high-end applications.
<b>Authoritative testing methods</b>	Tests involving microstructure, mechanical properties, surface defects, etc. are all supported by a complete method system.

### 4. Certification and Matching Recommendations for Tungsten Alloy Tubes Exported to the United States

compliance requirements of the US market for tungsten alloy tubes , domestic manufacturers are advised to:

1. **Product standard comparison** : ASTM B777, MIL-T-21014C and other standards should be clearly adopted or referenced in the technical specifications;
2. **Provide quality inspection reports in Chinese and English** : including chemical composition analysis, mechanical properties test, ultrasonic testing records, etc.
3. **Obtain third-party test reports** : such as ASTM standard test certificates issued by SGS, BV and other institutions;
4. **Military industry registration and filing** : If the customer is involved in the US military supply chain, relevant ITAR compliance qualifications must be obtained .

### V. Conclusion

The US ASTM and MIL standard systems provide comprehensive support for the standardized production and international trade of tungsten alloy tubes. While there is no single, dedicated standard for "tungsten alloy tubes," the relevant specifications are sufficient to guide production, inspection, and quality control. Chinese tungsten alloy tube manufacturers, when exploring the American market, must thoroughly understand and strictly adhere to key standards such as ASTM B777 and MIL-T-21014 to achieve steady breakthroughs and sustainable growth in the global high-end materials supply chain.

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### 7.3 EU and ISO international standards for tungsten alloy tubes

Tungsten Heavy Alloy Tubes (Tungsten Heavy Alloy Tubes), an advanced material with high density, high melting point, and excellent radiation and corrosion resistance, are widely used in aerospace, nuclear energy, medical protection, military, and high-end manufacturing. As the international market continues to demand higher levels of product consistency and traceability, the European Union (EN) and the International Organization for Standardization (ISO) have established comprehensive and stringent standards and specifications for the design, performance, safety, and environmental impact of tungsten alloy tubes. Understanding and mastering these internationally recognized standards is crucial for tungsten alloy tube manufacturers to engage in cross-border trade, technical cooperation, and quality system development.

#### 1. Related specifications of tungsten alloy tubes in the EU EN standard system

Although there is no independent provision specifically for "tungsten alloy tubes" in the EU EN standards, the general metal material and powder metallurgy product standard systems that can be referenced include:

##### 1. EN ISO 4499-1/2: Metallographic examination and microstructural analysis of cemented carbide

- It can be used for microstructural evaluation of tungsten alloy tubes, especially for quantitative description of the uniformity and grain morphology of sintered dense structure.
- Guide the metallographic sample preparation process and unify inspection terminology and rating methods.

##### 2. EN 10204: Testing and certification of metal products

- Enterprises are required to provide material inspection reports and certificates, which can serve as quality certificates for tungsten alloy tubes when they are exported.
- Including 2.1 (Declaration of Conformity), 3.1 (Third-Party Quality Certification) and other document forms.

##### 3. EN ISO 6506 / 6507 / 6508: Brinell, Vickers, and Rockwell hardness test standards

- Suitable for testing the hardness of the inner and outer walls of tungsten alloy tubes, often used in the finished product inspection stage.
- Clarify detailed requirements such as indentation load, holding time, and test surface treatment.

##### 4. EN ISO 6892: Tensile testing standard for metallic materials

- Suitable for evaluating the tensile strength, yield point, and elongation of tungsten alloy tubes and tubes, and suitable for hot-rolled, annealed, or sintered materials.

##### 5. EN ISO 6508-1: Rockwell hardness test for metals

- for high hardness tungsten alloy products and is suitable for local hardness measurement of small diameter and thin-walled tubes.

##### 6. EN ISO 9001: Quality Management System Requirements

- For tungsten alloy tube manufacturers exporting to the EU, implementing a quality control system that complies with ISO 9001 is one of the basic conditions for entering the market.

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## 2. Related specifications of tungsten alloy tubes under ISO international standard system

As the International Organization for Standardization, ISO publishes material and testing standards that are widely adopted by the world's high-end manufacturing industry. They are particularly authoritative in transnational certification systems, international bidding and standard comparisons.

### 1. ISO 2768 (Geometric Tolerance Standard)

- Provides general tolerance criteria for tungsten alloy tube inner diameter, outer diameter, wall thickness, ovality, length and other dimensional control.
- ISO 2768-m is commonly used as a machining standard for general precision requirements.

### 2. ISO 9001 / ISO 14001 / ISO 45001 three major management systems

- Enterprises need to pass third-party certification of quality management system (9001), environmental management system (14001) and occupational health and safety system (45001) to meet the requirements of international customers for compliant production .

### 3. ISO 6892-1/-2: Tensile test methods for metallic materials

- Guide the mechanical property testing of tungsten alloy tubes under different temperature environments, including room temperature (-1) and high temperature (-2) test processes.

### 4. ISO 6506/6507: Measurement of metal hardness

- Supports Brinell and Vickers hardness test methods, suitable for high-precision hardness evaluation of tungsten alloy tubes.

### 5. ISO 10110 series: optical component material and surface quality standards

- If tungsten alloy tubes are used in optical structures or nuclear instrument protection systems, this standard can be used as a reference for surface roughness, deformation, and flatness.

### 6. ISO 14062: Guidelines for Environmentally Friendly Product Design

- of tungsten alloy tubes during their life cycle, including energy consumption, recyclability, and environmentally friendly packaging.

## The significance of EU/ISO standards in the export of tungsten alloy tubes

Compliance Dimension	Key criteria	Compliance requirements	Application Scenario
Product Performance	ISO 6892, EN ISO 6507	Unified tensile and hardness tests	Customer acceptance and performance comparison
Dimensional tolerance	ISO 2768	Inner and outer diameter/wall thickness deviation control	Engineering support and system docking
Environmental regulations	ISO 14001 / REACH / RoHS	Comply with environmental regulations and contain no harmful substances	Export to EU, green certification
Quality System	ISO 9001, EN 10204	Document traceability and quality certification	Commercial Contract and Procurement Review
Defect Detection	ISO 9712 / EN 10308	Nondestructive testing qualifications and standardized operations	Acceptance in aviation and medical fields

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#### 4. Recommended Paths for Tungsten Alloy Tube Enterprises to Connect with International Standards

1. **Establish an international standard technical database** : organize and regularly update ISO and EN standard texts related to tungsten alloy tubes for internal reference and R&D guidance.
2. **Comparison analysis of product parameters and standards** : Establish a comparison table of product dimensions, performance and international standards to ensure that R&D and process links meet the requirements of the target market.
3. **Certification and third-party testing** :
  - o Passed ISO 9001/14001 system certification;
  - o We entrust SGS, TÜV, BV and other institutions to conduct composition, dimension and mechanical property tests under EN or ISO standards.
4. **Formulate enterprise internal control standards (Q/)** : Based on ISO/EN, formulate enterprise standards in combination with customer requirements and product actuality to form an effective quality assurance system.

#### V. Conclusion

The EU and ISO standards system provides systematic and highly authoritative technical specifications for the international trade, engineering applications, and product development of tungsten alloy tubes. These standards cover not only the various testing and performance assessment methods for tungsten alloy tubes, from raw materials to finished products, but also encompass compliance with environmental and safety regulations . For tungsten alloy tube manufacturers seeking to expand into the global market, particularly within the EU, a thorough understanding and active alignment with these standards will be crucial for building international competitiveness and achieving high-quality development.

#### Compliance Requirements for Tungsten Alloy Tubes (RoHS, REACH, MSDS)

Tungsten Heavy Alloy Tubes (Tungsten Heavy Alloy Tubes), a key metal material with high density, high strength, high temperature resistance, and corrosion resistance, are widely used in aerospace, nuclear energy, military, medical, and electronics industries. With the international market's increasing emphasis on environmental protection, safety, and sustainability, tungsten alloy tubes must strictly adhere to relevant environmental compliance regulations and standards during export and engineering use. In particular, regulations such as **RoHS** (Restriction of Hazardous Substances), **REACH** (Registration, Evaluation, Authorization and Restriction of Chemicals), and **MSDS** (Safety Data Sheets) constitute a fundamental barrier to market entry for tungsten alloy tube products within the EU and globally.

This section will systematically analyze the key points of environmental compliance for tungsten alloy tubes and propose implementation paths and management recommendations for enterprises.

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## 1. Analysis of the applicability of RoHS directive and tungsten alloy tubes

**RoHS** (Restriction of Hazardous Substances) is a European Union environmental regulation that restricts the use of certain hazardous substances in electrical and electronic products. Currently, RoHS 2.0 (2011/65/EU) and its revised versions are in effect.

### 1. RoHS restricted substances mainly include:

- Lead (Pb): < 0.1%
- Mercury (Hg): < 0.1%
- Cadmium (Cd): < 0.01%
- Hexavalent chromium (Cr6+): < 0.1%
- Polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs): < 0.1%
- Phthalates (DEHP, BBP, DBP, DIBP): < 0.1%

### 2. Risk factors in tungsten alloy tubes:

- Although tungsten alloy itself does not contain the above restricted elements, if lead-containing solder, plating or doping materials are used, it may exceed the limit;
- If tungsten alloy tubes are used as structural components, cooling components, or radiation shielding components of electronic devices in electronic and electrical systems, a RoHS compliance declaration is required.

### 3. Compliance requirements :

- Provide a RoHS Declaration of Conformity ( DoC ) stating that the product does not contain restricted substances;
- compliance audits on suppliers ;
- Support third-party test report (SGS, TÜV) certification.

## 2. REACH Regulation's Constraint Mechanism on Tungsten Alloy Tubes

**REACH** (Registration, Evaluation, Authorization and Restriction of Chemicals) is a comprehensive EU regulation on chemicals, covering the registration, evaluation, authorization and restriction of substances, and is widely applicable to products exported to the EU.

### 1. Application scope of tungsten alloy tube:

- REACH applies to all chemicals, mixtures and articles supplied to the EU market (Article);
- Tungsten alloy tubes are considered “articles” and if their ingredients contain substances of very high concern (SVHC) and the content exceeds 0.1%, they need to be reported and notified.

### 2. Risks associated with Substances of Very High Concern (SVHC):

- Certain adhesives, additives or surface treatment agents may contain SVHCs listed under REACH;
- If the content of ingredients such as beryllium, certain phthalates , polycyclic aromatic hydrocarbons (PAHs) exceeds the limit, it must be reported to the European Chemicals Agency (ECHA).

### 3. Enterprise response measures:

- Establish a REACH substance list and comparison mechanism;
- Require raw material suppliers to provide REACH compliance declarations;

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- Conduct risk assessment on process steps that may contain SVHCs (such as electroplating and coating);
- Complete REACH registration or notification procedures when necessary.

### 3. Requirements of MSDS Documents for Safe Delivery of Tungsten Alloy Tubes

MSDS (Material Safety Data Sheet) is an internationally accepted chemical safety information document that contains information such as the product's basic composition, physical and chemical properties, toxicity characteristics, environmental impacts, emergency measures, and transportation classification.

#### 1. Situations where MSDS needs to be prepared for tungsten alloy tubes :

- If the tungsten alloy tube is in powder form, wire form, or surface treated (e.g. electroplating, spraying, etc.), it may be considered a safety risk;
- If the company is involved in international transportation and cross-border supply chain cooperation, customers usually require it to provide MSDS;

#### 2. Key contents of MSDS include:

- Chemical composition and proportion (e.g. W 90%, Ni 6%, Fe 4%)
- Hazard identification: whether it is combustible dust, metal fume, etc.;
- Safety protection measures: protective equipment, leakage treatment, fire extinguishing methods, etc.;
- Storage and transportation precautions: sealing, moisture-proof, anti-static, classification and transportation code, etc.

#### 3. Recommendations for preparation and use:

- It is recommended to compile based on the GHS global unified classification standard;
- Provide bilingual versions in Chinese and English;
- Regularly updated and revised based on regulatory changes;
- Provide customers with digital and paper versions.

### 4. Recommendations on Environmental Compliance Management Process for Tungsten Alloy Tubes

Management	Recommended action	Core Files
Raw material screening	Establish a procurement list of non-toxic and harmless raw materials	RoHS Declaration of Compliance
Process control	Check for lead solder, heavy metal plating, benzene solvents, etc.	Process Compliance Report
Product Testing	Entrust a third-party agency to conduct RoHS/REACH testing	SGS/Intertek report
Regulatory monitoring	Track SVHC list updates and regulatory changes	Regulatory Update Database
Compliance output	Provide RoHS, REACH, MSDS and other documents required by customers	Compliance Files

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## V. Summary and Outlook

Against the backdrop of increasingly stringent global environmental regulations, the manufacturing and supply chain management of tungsten alloy tubes must gradually align with international standards such as **RoHS, REACH, and MSDS**. Companies must not only control raw material compliance at the source but also embed environmental requirements throughout the entire design, production, packaging, and transportation process to enhance their products' international market access and green image. As the concept of green manufacturing deepens, the environmental compliance of tungsten alloy tubes will become a crucial dimension in measuring a company's overall competitiveness.

Subsequently, tungsten alloy tube manufacturers can explore the construction of a full-process environmental compliance traceability system, integrating the RoHS material list, REACH notification status and MSDS shared document library through a digital platform to achieve efficient management and dynamic updating of compliance work, thereby taking the initiative in the fierce global market competition.

## 7.5 Quality System of Tungsten Alloy Tubes in Aviation, Nuclear Energy, Medical and Other Fields (AS9100, ISO13485)

Tungsten alloy tubes, with their **high density, strength, and excellent high-temperature and radiation resistance**, play an irreplaceable role in high-end manufacturing and high-reliability applications in aerospace, nuclear energy, and medical applications. These sectors place extremely stringent demands on product quality, safety, and consistency, forcing tungsten alloy tube manufacturers to strictly adhere to internationally recognized quality management systems to ensure their products can withstand long-term, stable service in complex or extreme environments.

This section focuses on the three key quality system standards applicable to tungsten alloy tube manufacturers: **AS9100 (aerospace quality management system)**, **ISO13485 (medical device quality management system)** and **ISO19443 (extended quality management system standard for the nuclear energy field)**, and analyzes their applicability, core elements and implementation recommendations.

### 1. AS9100: Quality Management System Requirements for Aerospace

**AS9100** is a quality management standard for the aviation, aerospace and defense industries issued by the International Aerospace Quality Group (IAQG). It is an expanded version of the ISO 9001 standard and adds special requirements for aerospace manufacturing.

#### 1. Applicability:

- Tungsten alloy tubes are widely used in aviation engines, satellites, rockets and other equipment as **aviation counterweights, inertial components, heat-resistant pipes or protective structural materials** ;

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- If the company is a first-tier or second-tier supplier in the aerospace industry chain, it must pass AS9100 certification before supplying goods.

## 2. Core content:

- Product Safety and Error Proofing;
- Risk Management (Risk-Based Thinking);
- Special process control (e.g., heat treatment, sintering, additive manufacturing );
- Supply chain management and change control;
- Traceability, non-conformity handling and corrective and preventive measures.

## 3. Implementation recommendations:

- Establish a complete documented quality system;
- Key personnel must undergo AS9100 internal audit and system training;
- Conduct process capability analysis and first article inspection (FAI) regularly;
- Introducing aviation tools such as Failure Mode and Effects Analysis (FMEA) and PPAP.

## 2. ISO 13485: Medical Device Quality Management System Standard

Tungsten alloy tubes are widely used in **radiotherapy positioning devices, shields, gamma-ray modulators, and medical counterweights**. Their stability, density, and non-magnetic properties make them particularly suitable for high-precision medical equipment. **ISO 13485** is an international quality system standard specifically for the design, manufacture, installation, and service of medical devices.

### 1. Applicable scenarios:

- If medical equipment manufacturers use tungsten alloy tubes for **radiation shielding, protective device components, and X-ray components**, the raw materials and structural parts must be sourced from suppliers that have passed ISO13485 certification.
- medical tungsten alloy tubes directly constitute part of a medical device, the relevant manufacturers must cooperate with registration, auditing and technical data review.

### 2. Requirements Highlights:

- Product life cycle management and risk control;
- Process verification and validation (such as irreversible processes such as sintering and rolling);
- File record keeping (Design History File);
- Process monitoring, internal audit and customer feedback mechanism;
- Adverse event reporting and recall program management.

### 3. Enterprise Countermeasures:

- Ensure product batch consistency and stability;
- Improve raw material inspection, process monitoring and factory records;
- Design changes require evaluation of potential medical impact and revalidation;
- Trace each batch of tungsten alloy tubes back to the original supply source and manufacturing process.

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### 3. ISO 19443: A quality management standard specifically for the nuclear energy sector (referenced to ISO 9001)

Tungsten alloy tubes **used in nuclear power equipment as radiation shielding tubes, structural components, or thermal conductivity system components** must meet the nuclear industry's higher safety, reliability, and traceability requirements. **ISO 19443** is an extension of ISO 9001 for the nuclear industry, specifically applicable to quality management for **nuclear facility suppliers**.

#### 1. Application features:

- Mainly applicable to suppliers of materials, components and services for **nuclear power plants, nuclear fuel cycles, nuclear reactors and related projects** ;
- Tungsten alloy tubes used for core supports, radiation sleeves, shielding components, etc. must comply with the full process control of this standard.

#### 2. Core control points:

- Safety culture is integrated into the quality management system;
- Product and service risk assessment mechanism;
- Traceability and documentation integrity;
- Conversion of customer requirements and implementation of regulatory clauses;
- Third-party witnessing and customer-specified verification activities.

### 4. Comparison and Adaptation Suggestions of the Three Major Systems

standard	Applicable areas	Key requirements	Typical Applications
AS9100	Aerospace	Product safety, traceability, and risk management	Satellite inertial components, space counterweights
ISO13485	medical devices	Process validation, adverse event reporting, and regulatory compliance	Radiotherapy protective sleeves, X-ray shielding components
ISO19443	nuclear energy industry	Safety culture, nuclear-grade quality control , and document integrity	Nuclear shielding tubes, irradiation components

## V. Summary and Outlook

As a highly engineered functional structural material, tungsten alloy tubes are no longer solely competitive based on performance indicators when entering **the high-end equipment manufacturing field** . They also require a systematic and sustainable quality management system. AS9100, ISO13485, and ISO19443, as globally recognized authoritative standards, have become the key to companies' entry.

For manufacturing companies, it is recommended to use ISO 9001 as the basis for quality management. On this basis, appropriate extended standards should be selected for the target industry to promote the upgrade of internal control systems, process transparency, batch traceability, and the deep integration of quality systems and market development, thereby laying a solid foundation for the industrialization and internationalization of tungsten alloy tubes.

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Subsequent suggestions include exploring the integrated construction of the quality system, horizontally integrating the three major standards, and realizing a common platform, modularization, and digital management of aviation, nuclear energy, and medical businesses, so that tungsten alloy tube products can truly achieve the international level of "high-end consistency, high quality and compliance ."

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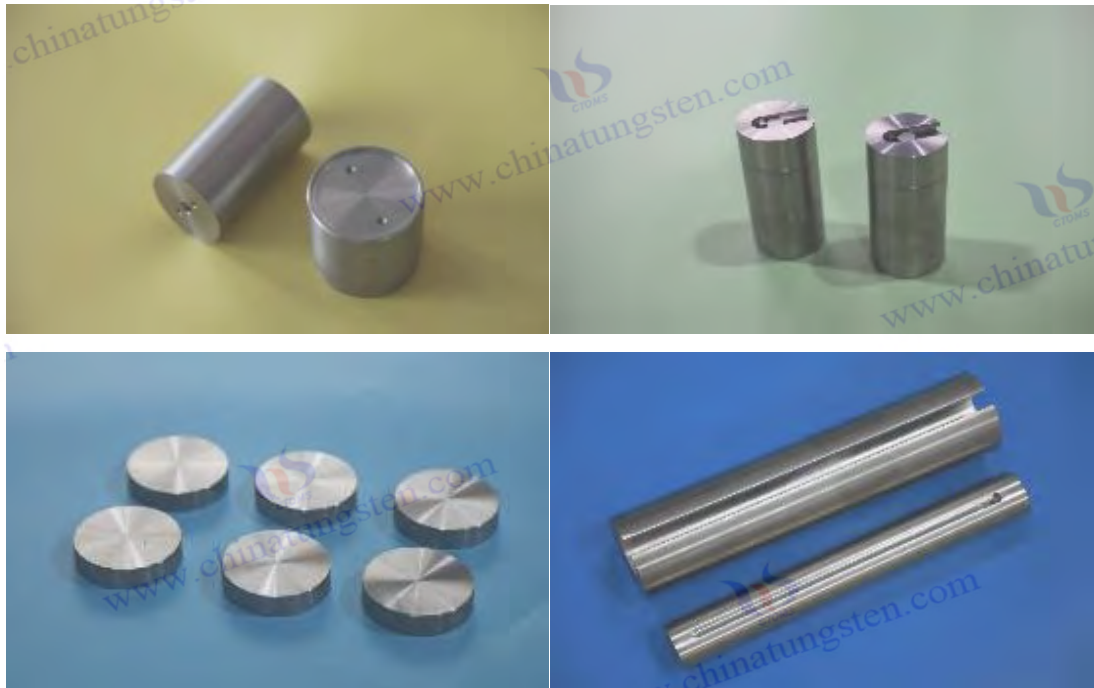
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Contact us

Email: [sales@chinatungsten.com](mailto:sales@chinatungsten.com)

Tel: +86 592 5129696

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[www.ctia.com.cn](http://www.ctia.com.cn)

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



## Chapter 8 Packaging, Storage and Transportation Specifications for Tungsten Alloy Tubes

### 8.1 Packaging Material Selection and Protection Design for Tungsten Alloy Tubes (Vacuum, Drying, and Buffering)

As a high-density, high-value, and brittle precision alloy product, tungsten alloy tubes place extremely high demands on packaging and protective systems during **production, storage, and international transportation**. Improper packaging can not only cause surface scratches, edge collisions, or structural deformation, but can also cause metal oxidation or contamination due to humid environments, impacting subsequent processing quality and end-use performance. Therefore, scientifically and systematically developing a packaging material system and protective design for tungsten alloy tubes is crucial for ensuring product quality and delivery reliability.

#### 1. Basic Principles of Tungsten Alloy Tube Packaging Design

1. **Compression and shock resistance** : Due to the heavy weight and brittle structure of tungsten alloy tubes, the packaging system must have sufficient shock-absorbing capacity to prevent damage caused by inertial collision during loading, unloading and transportation.
2. **Sealing and moisture-proofing** : Although tungsten alloy has good corrosion resistance, components such as nickel and copper in the alloy may still suffer from surface discoloration and slight oxidation under the action of moisture, so moisture-proof packaging must be done.

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3. **Clean and pollution-free materials** : Packaging materials must not release organic pollutants, sulfides, chlorides and other active chemical components to avoid affecting the surface cleanliness of the tungsten alloy tube.
4. **Comply with international transportation standards** : The packaging structure should be convenient for loading and customs clearance inspection in standard container units for sea, air and land transportation, and comply with international regulations such as RoHS and ISPM 15.

## 2. Common Packaging Material Types and Applicability

### 1. Inner protective material

Material	Function	Features
<i>Polyethylene film</i>	Airtight, slightly waterproof	Good flexibility, suitable for vacuum packaging
<i>Aluminum foil composite film</i>	Moisture-resistant and UV-resistant	Suitable for long-term storage and transportation, strong anti-aging performance
<i>Foam/EPE (Emerald Polyethylene)</i>	Buffering and preventing collision	Often wrapped around the inner wall of a single tungsten tube or casing
<i>Deoxidizer/Desiccant</i>	Moisture absorption and deoxygenation	Silica gel and molecular sieves can provide long-term protection

### 2. Middle layer buffer structure

- **Honeycomb paperboard or corrugated paper** : used to isolate the contact between tungsten alloy tubes, low cost, and customizable shape;
- **High-density EVA pads** : commonly used for positioning and protection of precision tungsten tubes , strong pressure resistance and die-cuttable .

### 3. Outer protective container

- **High-strength wooden box (IPPC logo)** : suitable for long-distance export and heavy-duty transportation, with a stable structure;
- **Aluminum alloy box or composite material box** : suitable for use with air express and high-end equipment;
- **Special tube supports for multiple tungsten alloy tubes** : Made of PE, ABS or aluminum alloy, they can achieve structural fixation, tube diameter alignment, and batch transportation.

### 3. Typical packaging combination examples

1. **Export-oriented tungsten alloy tube protection structure** (applicable to heavy-duty tubes >1m long):
  - Inner layer: vacuum packaging (aluminum-plastic composite film + desiccant)
  - Middle layer: EPE full package + single branch pipe support spacer

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- Outer layer: plywood reinforced wooden box + IPPC heat treatment + anti-tilt mark

## 2. Precision tungsten tube aviation accessories packaging solution :

- Inner layer: clean dust-free PE film + multi-layer foam separation
- Outer layer: Aluminum box or recyclable high-strength plastic box with lock
- Attachments: Laser label + factory inspection form + MSDS instruction manual

## 4. Considerations for Tungsten Alloy Tube Packaging Design

- **Single wrapping principle** : For high-precision and high-finish tungsten tubes, it is strictly prohibited to have multiple tubes in contact without spacing;
- **Standardized identification labels** : must include material name, specification model, batch number, production date, and quality tracking code;
- **Transport direction instructions and warnings** : The outer packaging should be labeled with bilingual Chinese and English labels such as "Fragile", "Do not stack", and "Moisture-proof";
- **Seismic performance verification** : For special applications (such as military and aviation tungsten alloy tubes), it is recommended to introduce simulated transportation tests (such as ISTA standards) into the packaging plan.

## 5. Future development direction of packaging technology

With the advancement of intelligent international logistics and green and low-carbon trends, tungsten alloy tube packaging design also presents the following development directions:

- **Recyclable packaging system** : Use reusable metal/plastic structure packaging utensils to reduce the waste of disposable materials;
- **Intelligent protective materials** : integrated temperature and humidity sensing tags and impact indicators to monitor the packaging environment in real time;
- **Full-process digital tracking** : Batch traceability, inventory management, and logistics information synchronization are achieved through RFID chips or QR code labels .

## summary

Tungsten alloy tube packaging is not only a means of physical protection but also a crucial link in the product quality chain. From material selection and protective structure design to detailed control of moisture, vibration, and contamination protection, it must be implemented throughout the entire process from production to final delivery. A standardized and scientific packaging system can effectively improve international product delivery capabilities, reduce transportation losses, and enhance customer satisfaction. It also demonstrates a company's expertise in product reliability and brand management.

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## 8.2 Storage Conditions and Anti-Corrosion and Anti-Oxidation Requirements for Tungsten Alloy Tubes

tungsten alloy tubes are widely used in high-end fields such as nuclear energy, military industry, aerospace, medical treatment, and electronic equipment. However, without effective environmental control and protective measures during storage, external factors such as humidity, temperature, and corrosive gases can easily lead to quality problems such as surface oxidation, corrosion, contamination, and discoloration, affecting subsequent processing performance and product life. Therefore, formulating scientific and reasonable storage regulations and establishing a standardized storage environment are crucial to ensuring the quality and stability of tungsten alloy tubes.

### 1. Basic Requirements for Tungsten Alloy Tube Storage Environment

#### 1. Temperature Control :

- The recommended storage temperature range is  $5^{\circ}\text{C} \sim 30^{\circ}\text{C}$ .
- Frequent and drastic temperature fluctuations should be avoided to prevent condensation and the adhesion of water vapor to the surface.

#### 2. Humidity Control :

- The relative humidity should be controlled at  $<60\%RH$ , and for long-term storage it is recommended not to exceed  $50\%RH$ .
- High humidity environment can easily induce micro-oxidation of alloys containing elements such as nickel and copper, which manifests as yellowing and dark spots.

#### 3. Gas environment requirements :

- The storage area should avoid contact with corrosive gases such as sulfide, chlorine, ammonia, acid mist, etc.
- Try to avoid placing tungsten alloy tubes near areas where strong acids, strong alkalis, solvents and other chemical raw materials are stored.

#### 4. Cleanliness requirements :

- The storage place should be kept clean, free of oil and dust, and fireworks are strictly prohibited.
- If conditions permit, a constant temperature and humidity clean warehouse can be set up for the dedicated storage of high-end tungsten alloy tubes.

### 2. Key Technical Points of Tungsten Alloy Tube Storage

#### 1. Vertical and horizontal storage options

- For medium and long tungsten alloy tubes with a length greater than 500mm:
  - It is recommended to store horizontally, using pipe supports, foam grooves or brackets to separate them to avoid bending and deformation;
- For high-precision short tubes or high-finish tungsten tubes:
  - can be stored in a vertical tube-type manner. The pipe wall must not directly contact the hard structure and should be supported by a soft cushion layer.

#### 2. Storage containers and isolation materials

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type	Recommended Materials	Features
<b>Lining packaging materials</b>	Pearl cotton, polyethylene film, sulfur-free paper	Scratch-resistant, moisture-proof, clean and non-corrosive
<b>Storage tube/rack</b>	Stainless steel, aluminum alloy, PVC plastic	Stable, easy to clean, anti-oxidation
<b>Shelf structure</b>	Wood/Steel Anti-Rust Coating	Layered and numbered management, moisture-proof board bottom pad to prevent moisture

### 3. Storage period and maintenance of tungsten alloy tubes

Storage period	Recommended environmental conditions	Status check cycle	Precautions
Short-term (<3 months)	Normal temperature and humidity, sealed and dry	Once a month	Please reseal after opening
Medium term (3-12 months)	Constant temperature and humidity chamber, with desiccant	Once every two weeks	Try to use vacuum packaging
Long-term (>12 months)	Vacuum sealing + drying warehouse	Check the seal weekly	It is recommended to periodically turn over and replace the desiccant

### 4. Storage precautions under special environments

#### 1. Seaside/humid areas :

- A packaging layer should be added, preferably an aluminum-plastic composite airtight bag.
- Warehouses need to be equipped with industrial dehumidification equipment and maintained with ventilation.

#### 2. High altitude or cold regions :

- Pay attention to the condensation problem caused by temperature difference, and slowly increase the temperature to unseal it.

#### 3. Tungsten alloy tubes used in clean rooms :

- The storage area must meet the cleanliness level of Class 1000 or above;
- The stored materials should not shed dust or release organic volatiles.

### 5. Warehousing Management System and Traceability Recommendations

- Establish a **product number and inbound and outbound record system**, including material batch number, storage time, and usage destination;
- **inspect the appearance and oxidation status of tungsten alloy tubes** in stock ;
- Implement the **first-in-first-out (FIFO) management principle** to ensure inventory turnover.

### Summary

tungsten alloy tubes not only impacts their surface condition and structural integrity but also directly

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influences their adaptability to downstream processes and the reliability of the end product. Scientific and rational temperature and humidity management, corrosion-resistant packaging solutions, and standardized warehousing systems are essential for ensuring the quality of tungsten alloy tubes. As tungsten alloy materials increasingly find high-end applications, the professionalization and standardization of storage processes have become crucial components of a company's overall competitiveness.

### 8.3 International Transportation Specifications for Tungsten Alloy Tubes

Tungsten alloy tubes, as a precision structural material with high specific gravity, high melting point, corrosion resistance, and radiation resistance, are widely used in industries such as nuclear energy, military, aerospace, and medical protection, and their global trade continues to grow. Due to their high density and value, and the fact that some types of tungsten alloy tubes are used for military or sensitive purposes, international transportation must strictly adhere to the relevant regulations of various countries and international organizations to ensure the safety, compliance, and efficiency of cross-border movement of goods.

#### 1. Basis for Determining Whether Tungsten Alloy Tubes Are Controlled Items

Before international transportation, it is necessary to first determine whether the tungsten alloy tubes being transported are **dual-use items or military controlled products**. This will directly determine the complexity of the transportation process. The main criteria for judgment include:

##### 1. Alloy composition :

- If the tungsten alloy tube contains **strategic metals such as molybdenum , nickel, cobalt, rhenium, etc. in a specific proportion** and has special physical properties (such as radiation resistance or ultra-high density), it may be classified as restricted;

##### 2. Declaration of use :

- Tungsten alloy tubes used in the nuclear industry, weapon systems or satellite protection components usually need to be declared as sensitive materials;

##### 3. Relevant regulations :

- It involves regulations such as the Wassenaar Arrangement, the China Dual-Use Items and Technologies Export Control Regulations, the U.S. Export Administration Regulations (EAR), and the EU Dual-Use Regulation.

If goods are identified as sensitive goods, the exporter usually needs to apply for **an export license or provide an end-user certificate in advance**.

## II. Main modes of transportation and customs clearance requirements

### 1. Choose the mode of transport

Tungsten alloy tubes are usually shipped in the following ways based on weight, precision grade, shipping time and destination:

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Mode of transportation	Applicable situations	Features
Sea Freight	High-volume, cost-sensitive exports	Low freight, long cycle, need to strengthen moisture-proof
air transport	High value-added, small batch, urgent order	Fast transportation, high customs clearance requirements, and stricter packaging
Land transport (cross-border)	Asia/Neighboring Countries	Customs clearance is convenient, but you need to pay attention to border inspection policies

## 2. Import and export customs clearance documents

- **Commercial Invoice**
- **Packing List**
- **Bill of Lading / Air Waybill**
- **Certificate of Origin (CO)**
- **Material Certificate (MTC)/Product Manual**
- **Import and export license or dual-use approval (if applicable)**

Special note: If tungsten alloy tubes are used in military, nuclear energy, aviation and other fields, the customs of the destination country may require detailed technical parameter descriptions and end-user declarations.

## 3. International Standards for Packaging and Transportation of Tungsten Alloy Tubes

To ensure that the tungsten alloy tube does not deform, oxidize, or get damaged during long-distance transportation, its packaging must comply with international cargo transportation practices and standards:

### 1. Packaging design principles

- **Compression and impact resistance** : Use wooden boxes, metal barrels or honeycomb cartons containing cushioning materials such as EPE, foam, etc.
- **Moisture-proof and anti-oxidation** : vacuum packaging or adding desiccant, with waterproof film covering the outer layer;
- **Clear labeling** : clearly marked with "Tungsten Alloy Tubes", part number, weight, size, supplier, destination, precautions, etc.
- **Compliance label** : If it involves military use, a dual-use cargo transport label should be affixed .

### 2. Relevant international standards

- **UN Recommendations on the Transport of Dangerous Goods**
- **IATA Dangerous Goods Regulations (such as air transport)**
- **ISPM 15 (Export wooden box fumigation standard)**
- **ASTM B777 or GB/T 4169 packaging test specifications** (for tungsten alloy products)

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#### IV. Key points for risk prevention and control during transportation

Risk Type	Countermeasures
Collision/squash deformation	Adopt reinforced structural bracket/sleeve type separation structure
Corrosion in humid environments	Vacuum packaging + desiccant + moisture-proof indicator card
Customs detention of goods	Apply for export license and technical data filing in advance
Included in the sensitive list	Accurately declare product name/purpose/end user to avoid sanctions risks
Delivery delays	Select a stable logistics company and provide full tracking and customs clearance services

#### V. Typical Regulatory Cases in the Destination Country

- **Mainland China** : Tungsten products must be approved by the Ministry of Commerce before export and must be included in the "Dual-Use Items and Technologies Export License Catalogue".
- **United States** : EAR 99 or 600 Series controls may apply, and whether an export license is required depends on the properties and intended use of the alloy.
- **EU countries** : Must comply with the EU Dual-Use Regulation and REACH registration requirements.
- **India, Russia, the Middle East and other regions** : Some countries require the provision of terminal instructions for special alloy materials and increase security checks during the customs declaration stage.

#### summary

tungsten alloy tubes involves multiple compliance factors, including metal materials, strategic materials, and dual-use products. Companies organizing cross-border transportation must be highly sensitive to the policies of the destination country and establish comprehensive compliance procedures. Companies are advised to partner with **freight forwarders/customs brokers experienced in international metal trade**, and to maintain thorough records of packaging, declarations, licensing, and traceability to ensure the safety, efficiency, and compliance of tungsten alloy tubes during international transportation.

#### 8.4 Customs Supervision and License Application for Tungsten Alloy Tube Export

Tungsten alloy tubes, as a high-performance metal structural material, are widely used in high-end manufacturing fields such as nuclear energy, military industry, aerospace, medical treatment, and electronics. Some products also possess certain strategic material properties. Therefore, when exporting tungsten alloy tubes, companies must strictly comply with the customs regulations and relevant export control systems of the country in which they are located, and apply for appropriate export licenses and customs clearance filings based on the product's characteristics. Export procedures are particularly stringent when the tungsten alloy tubes are intended for sensitive applications or are dual-use items.

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## 1. Customs Commodity Code and Regulatory Attributes of Tungsten Alloy Tubes

When declaring for export, tungsten alloy tubes must be correctly classified according to the Customs Commodity Code (HS Code). Common classifications for exports from mainland China are:

- **8101.99.10** (Other tungsten and its products)
- **8101.99.90** (Other tungsten products, including alloys)

The specific code assignment is determined based on the product's **alloy composition, processing state (powder, tube, bar), and application**. Accurate classification can help avoid order returns, customs detentions, and illegal notifications.

Tungsten alloy tubes are often listed in the following regulatory attributes:

- **List of dual-use items and technologies** : if applicable to military or nuclear industries;
- **Strategic Materials List** : Contains specific high-density tungsten alloy tubes;
- **Export license management catalogue** : high-performance metal products that are subject to national export restrictions.

## 2. Main Types of Tungsten Alloy Tube Export Licenses

Depending on the policies of the exporting country (such as China), companies may need to apply for the following types of licenses before exporting tungsten alloy tubes:

License Name	Applicable Scenarios	competent authorities
<b>Export licenses for dual-use items and technologies</b>	Involving dual-use, sensitive purposes, and high-density tungsten alloys	Dual-Use Items Office of the Ministry of Commerce
<b>General Export License</b>	Non-sensitive tungsten alloy tubes, large amounts or special destinations	Department of Commerce or local Trade Promotion Bureau
<b>Military product export notification and filing</b>	Military tungsten alloy casings, guard plates, shell casings, etc.	State Administration of Science, Technology and Industry for National Defense
<b>End User Certificate</b>	Mandatory supporting materials for export to certain regions	Provided by foreign affairs or military customers

## 3. Tungsten Alloy Tube Export Declaration Process

1. **Product attribute confirmation** : determine whether the tungsten alloy tube is dual-use or strategic material;
2. **Advance filing/registration** :
  - Submit an application for export product registration to the competent commercial department;
  - Exporting enterprises must have import and export rights and qualifications to export dual-use items;
3. **License Application** :
  - Submit the Export License Application Form;

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- Attached: technical specifications, component analysis report, customer contract, end-user instructions, etc.;
- 4. **Review and Approval :**
  - The approval process generally takes 7–15 working days, but can take up to 30 days for certain products.
- 5. **License acquisition and export declaration :**
  - Only after obtaining permission can you submit formal customs declaration data to the China Electronic Port System;
  - Attach the license number and paper documents for your reference.

#### IV. Review Requirements for End Users and Applications of Tungsten Alloy Tubes

In order to prevent tungsten alloy tubes from flowing into informal channels or being diverted to military sensitive projects, the exporter must ensure that the customer and the end use are compliant :

- **End-user questionnaire :** customer name, address, and qualification certificate;
- **Description of use :** such as "for medical accelerator protective structure", "for scientific research experimental equipment", etc.
- **Non-re-export guarantee :** Signing a letter of commitment not to resell or divert for military purposes;
- **Orders involving the US/EU :** local re-export control regulations (such as EAR re-export regulations) must be complied with.

#### V. Special regulatory requirements in key countries or regions

Country/Region	Special regulatory points
USA	Involving EAR and ITAR regulations, some tungsten alloys require BIS approval
European Union	EU Council harmonization regulation on dual-use items
India/Middle East	For high-risk export destinations, it is necessary to focus on the end user and the flow of military defense.
Russia/Ukraine	Regions that may be currently sanctioned require a comprehensive risk assessment and compliance statement

#### VI. Risks and Legal Liabilities of Illegal Exports

If the export process of tungsten alloy tubes involves concealing the purpose, misreporting the product code, or exporting without permission, the company may face the following risks:

- **Administrative penalties :** fines, suspension of import and export qualifications;
- **Criminal liability :** suspected of illegal business operations, smuggling or endangering national security;
- **International sanctions risks :** inclusion in the overseas entity list, freezing of customer funds, or business interruption;
- **Loss of credibility :** affecting cooperative relationships with governments, customs, and multinational customers.

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## VII. Compliance Recommendations

1. **Establish a classification and identification mechanism for export items** and identify the properties of all tungsten alloy tube products;
2. **Deploy professional customs declaration and trade compliance personnel** who are familiar with export license and declaration operation procedures;
3. **Strengthen due diligence management of foreign customers** to ensure proper use and clear flow of funds;
4. **Cooperate with the competent authorities in post-export tracking and verification** , and keep complete sales records and document archives;
5. **Pay attention to international situations and policy changes** , and formulate response plans in advance (such as stocking up in advance and changing transportation channels).

### summary

tungsten alloy tubes are subject to multiple regulations during international export. Companies must accurately identify product attributes, apply for relevant export licenses in compliance with regulations , and complete customs declaration procedures in accordance with the law. Especially in today's increasingly complex international trade environment, tungsten alloy tube manufacturers and exporters must strengthen compliance management , prevent and control risks, and steadily advance global market expansion.

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

## CTIA GROUP LTD

### High-Density Tungsten Alloy Customization Service

CTIA GROUP LTD, a customization expert in high-density tungsten alloy design and production with 30 years of experience.

**Core advantages:** 30 years of experience: deeply familiar with tungsten alloy production, mature technology.

**Precision customization:** support high density (17-19 g/cm<sup>3</sup>), special performance, complex structure, super large and very small parts design and production.

**Quality cost:** optimized design, optimal mold and processing mode, excellent cost performance.

**Advanced capabilities:** advanced production equipment, RMI, ISO 9001 certification.

#### 100,000+ customers

Widely involved, covering aerospace, military industry, medical equipment, energy industry, sports and entertainment and other fields.

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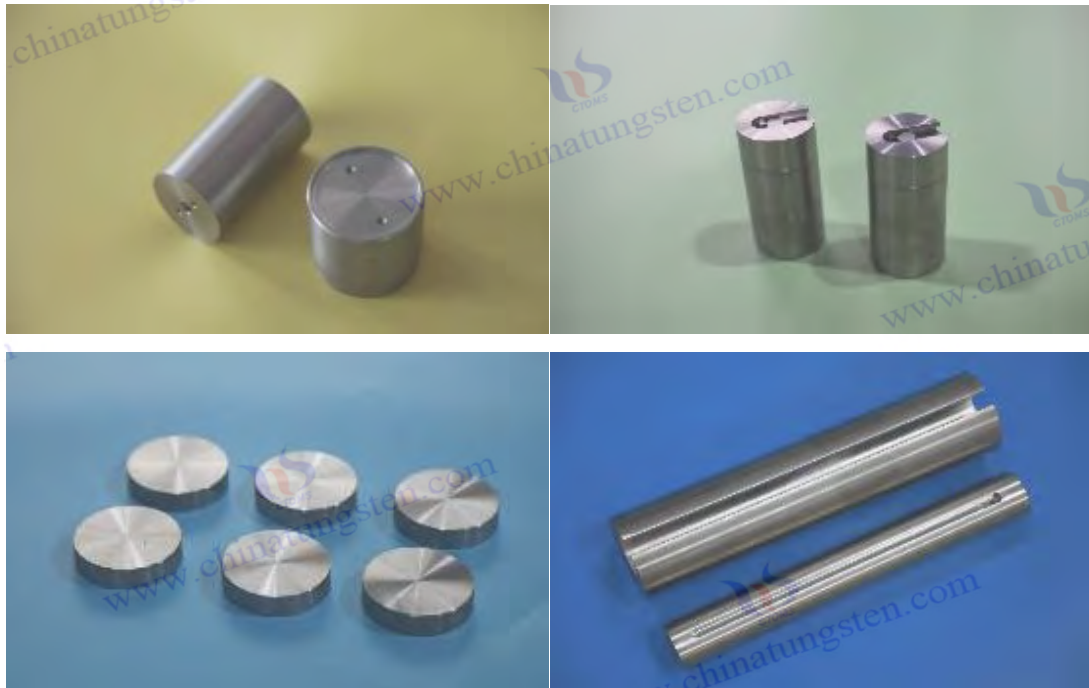
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电话/TEL: 0086 592 512 9696  
CTIAQCD-MA-E/P 2018-2024V  
[sales@chinatungsten.com](mailto:sales@chinatungsten.com)



Chapter 9 Industrial Structure and Market Trend of Tungsten Alloy Tube

9.1 Global Tungsten Resources Overview and Tungsten Alloy Pipe Industry Chain Analysis

As a key representative of high-performance, high-density metal materials, tungsten alloy tubes are widely used in key sectors such as nuclear energy, military industry, aerospace, medical treatment, and high-end equipment manufacturing. Their production relies on the rare and strategic resource of tungsten. The competitive landscape and development potential of the tungsten alloy tube industry are directly determined by the global reserves, mining distribution, processing capacity, and the coordinated development of the downstream industry chain .

1. Global tungsten resource distribution and reserves

Tungsten is a rare metal with extremely low abundance in the earth's crust. Its resources are mainly concentrated in a few countries. As of now, the world's tungsten reserves are estimated to be more than **3.5 million tons of metal tons** , of which reserves and production capacity are mainly concentrated in the following countries:

Country/Region	Reserves share	Main mining areas/characteristics
China	>50%	Dayu in Jiangxi, Yaogangxian in Hunan, Baiyin in Gansu, etc., are rich in resources and have complete industrial chains.
Russia	6–8%	The East Siberia and West Ural regions are rich in tungsten-molybdenum symbiotic mineral resources.

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Vietnam	5–6%	Nui Phao mining area is rich in tungsten, fluorite, molybdenum and bismuth polymetallic ores
Canada	4–5%	Mainly tungsten sand ore, with great resource potential but high mining cost
Bolivia, United Kingdom, Portugal, etc.	Small amount	There are multiple small and medium-sized ore bodies with regional development potential

Among them, China is not only **the world's largest tungsten resource owner**, but also the largest producer and exporter. Its resource development, mineral processing and purification, and tungsten deep processing technologies lead the world.

## 2. Raw Material Supply Chain of Tungsten Alloy Tube

tungsten alloy tubes mainly include **high-purity tungsten powder**, alloying elements (such as Ni, Fe, Cu), and a certain proportion of binder metal. The raw material supply chain mainly includes the following links:

1. **Tungsten ore mining and processing**: Wolframite ( $\text{FeWO}_4$ ) and scheelite ( $\text{CaWO}_4$ ) are obtained through flotation or gravity separation to obtain concentrate;
2. **tungsten compounds**: conversion of concentrate into APT (ammonium paratungstate) and tungstic acid ( $\text{H}_2\text{WO}_4$ );
3. **Reduction powder making**: APT obtains tungsten powder (W) through hydrogen reduction;
4. **Alloy ratio**: Add Ni, Fe or Cu powder to prepare alloy powder;
5. **Powder metallurgy preparation of pipes**: pressing, sintering, and machining.

Every link in the supply chain has a great impact on product performance, especially the particle size, purity and particle morphology of tungsten powder, which are key factors affecting the performance of tungsten alloy tubes.

## 3. Global Industrial Chain Layout of Tungsten Alloy Tube

tungsten alloy tubes can be divided into three major links: **upstream resources and basic raw materials, midstream forming and processing technology, and downstream application system integration**:

### (1) Upstream: Tungsten resource mining and powder manufacturing

- Representative companies: China Tungsten Online, CTIA GROUP, etc.
- Characteristics: Concentrated resources, restricted mining policies, and an oligopolistic trend.

### (2) Midstream: Tungsten alloy material preparation and pipe processing

- Representative companies: CTIA GROUP, Kennametal (US), Plansee (Austria), Mitsubishi Materials (Japan);
- Core technologies: isostatic pressing, precision sintering, inner hole processing and surface treatment.

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### (3) Downstream: military, aviation, medical and high-end manufacturing companies

- The application areas are constantly expanding, such as high-energy particle accelerator casings, inertial counterweight guide tubes, radiation protection casings, etc.
- Customers mainly focus on customization and certification, and have extremely high requirements for product consistency.

### 4. Global Market Status and Industry Focus of Tungsten Alloy Tubes

At present, the global tungsten alloy tube market presents the following characteristics:

1. **Due to high technical barriers and long certification cycles**, customers in the military and aerospace fields mostly adopt an "entry-level system";
2. **Production capacity is concentrated in a few high-tech companies**, such as China Tungsten Manufacturing and Germany's Plansee ;
3. **Most European and American countries rely on imported tungsten powder or semi-finished tungsten alloy tubes for further processing** ;
4. **The Asia-Pacific region has become a major processing, manufacturing and export base**, especially China, where high-density tungsten alloy tubes account for more than 70% of the world's total exports.

### 5. Constraints and Challenges of Tungsten Alloy Tube Industry

tungsten alloy tubes also faces a series of challenges:

- **Strengthened resource export controls** : For example, China has implemented export quotas on APT and tungsten powder;
- **Environmental regulations and rising energy costs** : The sintering process is highly energy-intensive, placing new demands on carbon emission control;
- **Technology transfer restrictions** : Technology related to military/nuclear tungsten tubes is still subject to export controls;
- **Supply chain stability risk** : Especially when the international situation is turbulent, the supply and demand of tungsten resources are prone to fluctuations.

### VI. Industrial Collaborative Development and Vertical Integration Trends

As demand for tungsten alloy tubes grows, leading companies are gradually developing vertically integrated strategies, connecting the entire process from mineral resources to high-end components to improve product stability, reduce costs, and gain control over end customers. Companies such as CTIA GROUP and Xiamen Tungsten New Energy are already integrating resources, materials, devices, and systems, driving the transformation of tungsten alloy tubes from "material output" to "functional component solution providers."

#### summary

Global tungsten resources are highly concentrated, with China in particular possessing systemic advantages in resources, technology, processing, and exports. As a key component for high-end applications, the industry chain for tungsten alloy tubes is trending towards global division of labor and regional collaboration. Looking ahead, a company's position in the tungsten alloy tube industry

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will be determined by its comprehensive capabilities in resource security, technological breakthroughs, and market expansion . The next section will further analyze the market size, growth trends, and the competitive landscape among major players.

## 9.2 Market Capacity and Demand Growth Trend Forecast for Tungsten Alloy Tubes

Tungsten alloy tubes, a precision metal structural material with high density, high strength, high temperature resistance, and radiation resistance, are seeing an ever-expanding application in defense, nuclear energy, aerospace, medical, electronics, industrial molds, and other fields. Market demands for performance indicators and product diversification are also increasing year by year. Against the backdrop of global manufacturing technology upgrades and surging demand for high-performance functional materials, the tungsten alloy tube industry is experiencing a golden window of structural growth.

### 1. Current status of global tungsten alloy tube market capacity

According to multiple research data and information disclosed by industry chain companies , the global tungsten alloy tube market is expected to reach an annual output value of approximately **US\$1.2-1.5 billion by 2025** , with high-end tubes for the military and nuclear industries accounting for over 40%. As the world's largest tungsten resource holder, China's tungsten alloy tube production capacity accounts for **over 65%** of global output , giving it a competitive advantage in both the low-end and mid-to-high-end markets.

area	Annual demand scale (estimated)	Application Features
Chinese mainland	\$600–800 million	Military industry, nuclear power, aviation, medical treatment, precision manufacturing
North America	\$200–300 million	Mainly nuclear energy and military industry, with high dependence on imports
Europe	\$150–200 million	Medical and protective materials, aerospace industry
Other Asia Pacific	\$100 million+	South Korea and Japan have significant use in semiconductors and optical structures.
Middle East/Africa/South America	< \$0.5 billion	Local application initial stage

### 2. Tungsten alloy tubes’ main downstream applications drive growth

- for defense equipment upgrades**  
, including armor-piercing projectiles, inertial guide tubes, and protective structures, is driving the strategic importance of high-density tungsten alloy tubes in the military industry. The related sector is expected to grow at an **average annual rate of over 8%** from 2025 to 2030 .
- Tungsten alloy tubes are an excellent alternative to lead and molybdenum tubes for **the expansion of nuclear energy and radiation protection systems due to their superior**

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**resistance to neutrons and gamma rays**

. With the global restart of nuclear energy and the commercialization of small reactors, demand is expected to continue to expand.

3. **increasing**

**demand for high-performance structural parts in the aerospace industry chain**, such as high-temperature guide tubes, inertial transmission components, and flight control kits, is driving the development of tungsten alloy tubes towards lightweight and functionalization.

4. **The demand for medical radiotherapy equipment is expanding.**

Medical protection, gamma ray collimators, electron beam accelerators, etc. have extremely high requirements for the size accuracy and purity of tungsten tubes , and the high-end market has huge potential.

5. **High-end equipment and electronic thermal control systems are developing**

in the fields of communication heat dissipation, laser cooling, chip packaging, etc. Tungsten alloy tubes have good thermal conductivity and shielding properties and are gradually entering consumer and industrial thermal management applications.

**3. Tungsten Alloy Tube Market Annual Growth Rate Forecast (2025–2030)**

Comprehensive industry surveys, the International Materials Development Model (IMDF) and major companies' planning estimates:

years	Global market size (US\$ billion)	Average annual growth rate (CAGR)
2025	12–15	Base year
2026	13.5–17	10–12%
2027	15–19	11–13%
2028	17–22	12–14%
2030	20–26	12–15% (compound growth)

Among them, **the medical and nuclear energy fields** will be the two fastest growing sub-sectors in the future, followed by aerospace counterweights and thermal conductivity applications of electronic equipment.

**4. Key factors affecting market expansion**

Influencing factors	Positive effect	Potential constraints
<b>Technological advancement</b>	Enhanced size control and improved density	High requirements for equipment and talent
<b>Policy support</b>	Defense and nuclear industries drive demand release	Exports are affected by international political factors
<b>Industrial collaboration</b>	Connecting upstream and downstream will help scale development	High initial investment cost and long certification cycle
<b>Resource guarantee</b>	China holds the dominant position in resources	Tungsten price fluctuations affect product costs

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## 5. Conclusion and Trend Analysis

In summary, the tungsten alloy tube market is currently being driven by both technological upgrades and the expansion of high-end applications. Driven particularly by carbon neutrality, military modernization, miniaturized nuclear power equipment, and the global growth of medical imaging equipment, it is expected to maintain **an average double-digit annual growth rate over the next five years**, gradually evolving towards intelligent manufacturing and functional integration. Companies that master high-precision forming technologies and high-end customer certification capabilities will stand out in this round of industry expansion.

## 9.3 Introduction to CTIA GROUP Tungsten Alloy Tube

CTIA GROUP, a key player in China's new materials sector, is an advanced manufacturing enterprise specializing in the research, development, production, and sales of high-performance tungsten-based materials and their further processed products. The company possesses core competitiveness and industrialization capabilities, particularly in tungsten alloy tubing. Leveraging China's abundant tungsten resources and strong foundation in powder metallurgy, the company integrates upstream and downstream tungsten material resources to create a comprehensive supply chain, from raw material preparation, alloy design, precision forming, to end-use applications. The company is dedicated to serving high-end equipment manufacturing, nuclear power protection, medical radiation protection, military inertial components, aerospace counterweights, and high-temperature structural components.

### 1. Features of CTIA GROUP Tungsten Alloy Tube

CTIA GROUP's tungsten alloy tube products utilize advanced powder metallurgy technology combined with die pressing, isostatic pressing, precision sintering, and heat treatment processes. They offer stable performance, a comprehensive range of products, and the following significant advantages:

- **High density and dimensional precision control** : Density can reach 18.8–19.2 g/cm<sup>3</sup>, with uniform wall thickness and excellent internal and external coaxiality control, meeting the requirements of high-precision accessory assembly.
- **Excellent mechanical and thermophysical properties** : The product has good strength, toughness, thermal conductivity and high-temperature stability, and can serve for a long time under extreme conditions such as high heat flux and strong radiation.
- **Strong customizability** : CTIA GROUP supports customized processing of different alloy systems (such as W-Ni-Fe, W-Ni-Cu), various specifications and sizes (outer diameter ranging from 3 mm to 200 mm), and special-purpose tungsten alloy tubes (hollow inertial parts, micro-walled flow guide tubes, etc.) according to customer needs.
- **Mature internal and external surface treatment** : polishing, electrolytic treatment, chemical plating or PVD coating are used to significantly improve surface quality, corrosion resistance and radiation resistance.

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2. Representative tungsten alloy tube series products

Series Model	Alloy system	Outer diameter range	Application Directions
ZW-TG90	W-Ni-Fe	Φ6–Φ100 mm	Military armor-piercing, inertial counterweight
ZW-TG95	W-Ni-Cu	Φ3–Φ60 mm	Medical protection, nuclear energy structure
ZW-HHT	High temperature alloy	Φ10–Φ200 mm	High temperature pipes, thermal field conduits
ZW-MP	Microtube precision type	Φ3–Φ20 mm, wall thickness <0.5 mm	Electronic heat pipe, optical collimation

3. Application Cases and Market Layout

- Nuclear energy field** : The high-density tungsten alloy casing provided by CTIA GROUP is widely used in various types of neutron protection components and structural reinforcement tubes. Its performance indicators meet the requirements of CNNC and international nuclear power equipment suppliers.
- Medical radiotherapy** : Provide tungsten alloy tube components with precise inner diameter control and high radiation absorption efficiency for radiotherapy positioning systems and beam shaping devices.
- Aerospace inertial components and nozzles** : The products have been equipped with various high-precision inertial navigation flight control systems and participated in many major national aerospace missions, meeting the needs of high-load and high-intensity working conditions.
- Export business** : CTIA GROUP's tungsten alloy pipes are exported to Europe, America, Japan, South Korea, Southeast Asia and other countries and regions. Some products have passed the requirements of ASTM B777 and ISO 9001/AS9100 quality certification systems.

4. Technology R&D and Production Capacity

- R&D system** : It has established a "Tungsten-based Alloy Pipe Engineering Technology Research Center" and has built joint laboratories with universities such as Central South University and Hunan University, and continues to make efforts in alloy design, densification technology, welding forming and other directions.
- Equipment Capabilities** : Equipped with multiple sets of high-power isostatic pressing equipment, intelligent powder mixing systems, vacuum sintering furnaces, CNC internal and external grinders, and laser precision measurement and control systems, the company can achieve an annual output of nearly 100 tons of tungsten alloy pipes.
- Smart manufacturing transformation** : CTIA GROUP has deployed a digital MES system and quality traceability platform to promote the intelligent, standardized and traceable management of tungsten alloy pipe manufacturing.

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## V. Future Development Direction

CTIA GROUP is continuously expanding the applicability of tungsten alloy tubes in emerging application scenarios, with key areas including:

- Small modular reactor tungsten tube structural parts
- conductivity tungsten tube cooling unit for 5G and AI servers
- Special ballistic structure high impact tungsten alloy sleeve
- tungsten alloy porous conduit for high-strength electromagnetic shielding

At the same time, the company is also committed to the research, development and promotion of green manufacturing processes for tungsten alloys (ammonia-free sintering, green annealing, etc.), and to promoting the upgrading of tungsten-based pipe products to "low carbonization, high reliability and functionality".

**Summary:** CTIA GROUP has formed a complete closed-loop system in the field of tungsten alloy tubes, from material research and development, product manufacturing to customer customized services. In the future, it will continue to take "intelligently manufacturing high-performance tungsten alloys and serving the country's high-end equipment" as its mission, promote tungsten alloy tubes to achieve high value-added applications in multiple fields, and consolidate its leading position in the global tungsten alloy precision manufacturing field.

## 9.4 Tungsten Alloy Tube Raw Material Price Fluctuation and Cost Structure Impact

As a representative example of high-performance tungsten-based materials, the manufacturing cost of tungsten alloy tubes is influenced by a variety of factors, with raw material price fluctuations being particularly critical. Due to the strategic resource nature and scarcity of tungsten, and the fact that tungsten alloy tubes are typically manufactured using high-purity tungsten powder and binder metals such as nickel, iron, and copper, their cost structure is extremely sensitive to raw material market conditions. Fluctuations in raw material prices not only directly determine the sales price and profit margin of tungsten alloy tubes, but also, to a certain extent, impact the product's international competitiveness and the company's operational stability.

### 1. Characteristics of tungsten raw material price fluctuations

#### 1. Resource scarcity drives high prices.

Tungsten is listed as a key mineral resource in many countries, with its proven reserves primarily concentrated in China, Russia, Canada, and Vietnam. China holds a monopoly position, accounting for over 65% of the global reserves and production. Consequently, domestic and international tungsten concentrate supply controls, environmental policy changes, and export quota management all significantly impact tungsten prices.

#### 2. cyclical

fluctuations, such as a surge in tungsten concentrate prices in 2011 due to the rare earth industry regulation and production restrictions. From 2020 to 2023, tungsten prices experienced repeated irrational increases due to the pandemic, energy crises, and

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international trade frictions. Furthermore, short-term surges in demand from certain downstream industries (such as defense and nuclear energy) can also lead to supply shortages and periodic price anomalies.

### 3. With the significant price linkage effect of metals,

price fluctuations of commonly used binder metals in tungsten alloy tubes, such as nickel, copper, and iron, will also have a cumulative impact on the overall cost structure. Nickel prices are often driven by fluctuations in the stainless steel industry and new energy battery materials, while copper is closely related to global infrastructure investment. Although the fluctuation range of iron powder is relatively small, it cannot be ignored in large-scale mixing ratios.

## 2. Cost Structure of Tungsten Alloy Tube

According to the production process and raw material consumption analysis of typical tungsten alloy tubes, its cost structure can be roughly divided into the following parts:

Cost Items	Proportion range	illustrate
Tungsten powder raw material cost	40%–55%	Depends on the tungsten content in the alloy (usually 85–97%) and the market price at the time of purchase
Bonding metal (Ni/Cu/Fe)	10%–20%	Alloy tubes with high nickel content (such as high-density W-Ni alloy) account for a large proportion
Processing and manufacturing costs	15%–25%	Including molding/isostatic pressing, sintering, heat treatment and finishing
Energy and auxiliary material costs	5%–10%	Mainly vacuum sintering, power consumption and cooling gas, etc.
Management, logistics and labor costs	5%–10%	Related to enterprise size and degree of automation

It can be seen that the price of raw materials, especially tungsten powder, is the dominant factor. Once the price of tungsten powder rises by 30%, the overall manufacturing cost will increase by about 15%-20%.

### 3. Typical cases of the impact of raw material price fluctuations on costs

For example, from the fourth quarter of 2022 to mid-2023, the market price of tungsten powder rose from 260 yuan/kg to 300 yuan/kg, an increase of approximately 15.4%. Taking tungsten alloy tubes with 95% tungsten content as an example, if the raw material purchase volume is 100 tons, this fluctuation will lead to an increase in the cost per ton of alloy :

- **Increase =  $(300-260) \times 95\% = 38 \text{ yuan/kg} \times 1000\text{kg} = 38,000 \text{ yuan/ton}$**
- **Change in percentage = Raw material costs increased by approximately 14%–18%, and overall manufacturing costs increased by approximately 10%**

Such fluctuations have a significant impact on order profits, especially on small and medium-sized enterprises or export-oriented enterprises with long order cycles.

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#### 4. Response Strategies of Tungsten Alloy Tube Enterprises

In order to reduce the impact of raw material fluctuations on cost structure, tungsten alloy tube manufacturers often adopt the following strategies:

- 1. Establish a raw material reserve mechanism and strategic procurement agreement.**  
**By signing long-term supply agreements with large mining companies or participating in the integration of**  
tungsten resources within the group , we can lock in key raw material prices in advance and establish strategic reserves to reduce risk exposure.
- 2. Optimize product structure and alloy design**  
by adjusting alloy ratios, such as reducing some nickel content, using low-cost iron to replace part of copper, etc., to reduce the proportion of raw materials per unit weight, and develop more medium-density/functional products to share market pressure.
- 3. Improve process efficiency and energy consumption control in the manufacturing process**  
by introducing automated forming, intelligent sintering and finishing systems, reduce processing allowances and energy costs, and lower energy consumption per unit product while ensuring quality.
- 4. the price linkage mechanism and flexible contract terms design**  
can be used to link price changes with the raw material market by adding a price adjustment clause to the contract, thereby protecting the company's profit margin.

#### V. Conclusion

Overall, the cost structure of tungsten alloy tubes is highly sensitive to fluctuations in raw material prices. The scarcity and strategic nature of tungsten resources also make prices susceptible to policy, supply and demand, and international trends. As companies like CTIA GROUP continue to invest in green tungsten extraction processes, renewable resource utilization, and intelligent manufacturing, their ability to cope with cost fluctuations will continue to strengthen, driving tungsten alloy tube products towards higher performance, wider applications, and greater added value.

#### 9.5 Emerging Demand and Policy Direction for Tungsten Alloy Tubes in High-end Manufacturing

As the new round of scientific and technological revolution and industrial transformation deepens, high-end manufacturing industries, represented by aerospace, nuclear energy development, high-end medical equipment, semiconductor manufacturing, and the defense industry, are placing higher demands on advanced materials for greater integration and extreme service capabilities. Tungsten alloy tubes, due to their superior high specific gravity, high strength, high-temperature stability, and radiation resistance, are an ideal choice for many key components. Their potential for application in future high-end manufacturing is constantly being explored, and they are receiving high attention and strategic guidance from national policies.

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## **1. Specific demand trends for tungsten alloy tubes in emerging high-end manufacturing fields**

### **1. Aerospace and satellite propulsion systems**

Spacecraft, exploration satellites, manned spacecraft, and other systems require extremely high thermal stability and shape accuracy for components such as high-temperature gas flow guidance, plasma encapsulation, and attitude control. Tungsten alloy tubes, used as thruster heat flow tubes, high-speed gas channels, and inertial flywheel housings, excel in ultra-high temperature, vacuum, and intense thermal cycling environments, and are becoming a key material to replace traditional stainless steel and titanium alloys.

### **2. Nuclear energy and fusion energy technology**

In nuclear fission and fusion reactors, tungsten alloy tubes are widely used in cladding materials, neutron shielding sleeves, liquid metal cooling tubes, and other parts. They are required to have excellent neutron radiation resistance, thermal conductivity, and corrosion resistance. In particular, the chemical inertness and thermodynamic stability of tungsten alloy tubes are their unique advantages in liquid lithium, helium, and sodium cooling systems.

### **3. High-end medical equipment**

In radiotherapy equipment, particle accelerators, gamma knife housings, and precision target positioning components, tungsten alloy tubes, with their high density, anti-scattering properties, and excellent formability, effectively absorb radiation, shield side effects, and ensure structural stability. As radiotherapy equipment transitions from 2D to 3D precision treatment, higher requirements are placed on dimensional accuracy and magnetic field shielding capabilities.

### **4. Semiconductor equipment and electronics industry**

tubes are used in electron beam channels, deposition reactors, and high-energy particle beam control devices in high-vacuum, strong magnetic, and thermal shock environments. They require extremely high deformation stability, thermal conductivity, and electrical neutrality to avoid electric field disturbances and hot spot accumulation. Tungsten alloy tubes are also gradually entering the chip packaging thermal conductivity tube and micro-heat sink applications, ushering in opportunities for mass production.

### **5. Green energy and hydrogen equipment**

In high-temperature fuel cells and hydrogen storage and transportation systems, tungsten alloy tubes have excellent resistance to hydrogen embrittlement and thermal-chemical stability, and are expected to serve as key channel materials for efficient hydrogen storage and heat exchange in the future, meeting the demand for high-performance structural parts in green and low-carbon industries.

## **II. Policy Guidance and Support for National Strategies**

### **1. The promotion of the national policy of “strengthening the foundation and consolidating the supply chain”**

In recent years, the Chinese government has attached great importance to the bottleneck problem of key basic materials. As one of the country's key strategic rare metals, tungsten alloy has been explicitly included in core policies such as the "Strategic Mineral Resources Plan" and the "Basic Materials Shortcomings Action Plan." Tungsten alloy pipes, due to their wide application and high technical barriers, have become a key research area in the "strengthening and supplementing supply

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chains" initiative. Leading enterprises are encouraged to collaborate on key issues and develop high-performance product alternatives.

## **2. Support for energy-saving substitution of high-density materials under the background of "dual carbon"**

Tungsten alloy tubes offer far superior material efficiency in radiation shielding, protection, and thermal conductivity compared to traditional lead, steel, or high-alloy stainless steel. They facilitate lightweight, long-life, and high-thermal-efficiency applications, offering a natural advantage in energy conservation, emission reduction, and green manufacturing. Many local governments have introduced special incentives to support the replacement of traditional high-energy-consuming metallurgical components with tungsten alloy tubes, promoting green transformation.

## **3. Military-civilian integration policies encourage the expansion of high-end materials into civilian applications**

China encourages the transfer of military specialty materials technology to civilian applications. Tungsten alloy tubes, with proven experience in military inertial components, ammunition coatings, and catheter protection, are gradually expanding into high-value-added markets such as industrial instrumentation, electronic equipment, and medical structural components. With this policy support, a number of high-end materials companies have implemented production line upgrades and technology transfer, accelerating their marketization.

## **4. Construction of major scientific and technological projects and core experimental platforms**

tube-related research projects are extensively covered in the 14th Five-Year Plan's science and technology projects, the "First Batch Demonstration Project for Key New Materials," and the military-civilian collaborative research program, encompassing service performance research, composite process development, and simulation of complex service conditions. The China Academy of Engineering Physics, the Fifth Academy of China Aerospace Science and Technology, China National Nuclear Corporation, and China General Nuclear Power Group, among others, have already initiated systematic research and development, fostering a closed-loop ecosystem driven by application.

## **3. Conclusion: The strategic value of tungsten alloy tube industry continues to rise**

Against the backdrop of high-end manufacturing upgrades, technological security safeguards, and the restructuring of the global supply chain, tungsten alloy tubes are experiencing a new surge in industrial demand. As performance requirements continue to rise, tungsten alloy tubes will play a key role in achieving more refined structural control, more complex composite functions, and more demanding service environments. For materials companies, closely following policy guidance, strengthening application development, and overcoming process bottlenecks will be key to seizing the strategic opportunities presented by tungsten alloy tubes and achieving both technological and market advancements.

## **Technical Barriers and In-depth Development Paths of Tungsten Alloy Tube Industry**

tungsten alloy tubes hold a strategically important position in the nuclear, aerospace, military, medical, and electronics industries. However, the tungsten alloy tube industry is not a fully open

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market, characterized by extremely high technical barriers and a complex industrial chain. It has long been dominated by a small number of advanced companies and research institutions. Companies seeking to enter or enhance their tungsten alloy tube manufacturing capabilities must thoroughly understand the core barriers of each link in the industry chain and develop a multi-dimensional development path to achieve a closed-loop innovation system from raw material preparation to high-end products.

## 1. Key technical barriers of tungsten alloy tube industry

### 1. High-purity tungsten powder and alloy powder preparation technology

tungsten alloy tube performance lie in the purity, particle size distribution, sphericity, and oxygen content of the raw powder. Currently, the production of high-purity spherical tungsten powder still relies on complex reduction, atomization, or plasma spheroidization techniques, requiring high equipment investment, high-precision process control, and stringent yield requirements. Some core equipment and process control systems are still monopolized by foreign technology.

### 2. High-density forming and tubular structure pressing process

tungsten alloy tubes must possess a hollow structure during the forming stage. Mold design requires precise calculation of inner and outer diameter shrinkage. Simultaneously, the molding, cold isostatic pressing, or hot isostatic pressing processes must produce a dense, crack-free billet. This places extremely high demands on the equipment's pressure capacity, powder fluidity, and lubricant control.

### 3. High temperature sintering and controlled atmosphere densification technology

Tungsten alloy tubes must be sintered at temperatures between 1400 and 1600°C, with strictly controlled atmosphere type (hydrogen, inert gas, etc.) and oxygen partial pressure. Some high-end tungsten alloy tubes require sintering in a vacuum- micropressure -hydrogen atmosphere, supplemented by a secondary hot isostatic pressing (HIP) process to increase density. This process presents bottlenecks in terms of precision and safety risks.

### 4. Deep hole finishing and surface treatment capabilities for tubular parts

tungsten alloy tubes is a major obstacle to current technology. Traditional turning and grinding processes have difficulty reaching deep holes or maintaining inner wall concentricity and surface roughness. Specialized processes such as high-frequency vibration grinding, chemical polishing, and ultrasonic-assisted machining are required. Furthermore, electroplating, PVD coating, and anti-oxidation coating systems for the inner and outer walls also place extremely high demands on the production environment.

### 5. The cross-domain product certification and service evaluation system is not sound

Tungsten alloy tubes are widely used in high-risk applications such as nuclear radiation shielding, plasma propulsion tubes, and medical radiotherapy components. These applications often face complex requirements, including radiation stability, thermal fatigue, magnetic interference, and corrosion resistance. However, the lack of a comprehensive system of evaluation equipment, experimental methods, and testing standards has limited the rapid adoption of these products.

## 2. The in-depth development path of tungsten alloy tube industry

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tube industry system with sustainable competitiveness , it is necessary to advance from raw materials, processes, equipment, evaluation systems to application development at multiple levels. The following are several core directions:

**1. Vertically integrate the resource chain to create a closed loop from raw materials to pipe making**

Strengthen the integration of tungsten concentrate purification, tungsten powder spheroidization , alloying powder preparation and regeneration and recovery to form a low-cost, highly consistent powder supply chain. At the same time, promote the domestic substitution of independent sintering equipment, isostatic pressing machines, and pipe cold rolling equipment to reduce systemic dependence.

**2. High-performance tungsten alloy design and material system innovation**

Conduct multi-scale, multi-element alloy design, develop new pipe alloy systems such as W-Ni-Fe-Cr, W-Ni-Co, and W-Cu-Re, and enhance composite properties such as thermal and electrical conductivity, corrosion resistance, and magnetic interference resistance. Introduce microalloying and nanoparticle dispersion strengthening mechanisms to improve structural uniformity and long-term service stability.

**3. Build a high-end manufacturing platform and intelligent process chain**

Promote the development of intelligent pressing and hollow forming equipment for tungsten alloy tubes, establish an integrated production line of precise temperature control, plasma-assisted sintering, and HIP, combine industrial AI and sensor networks to conduct real-time prediction and feedback on microstructure, density, and porosity, and create "visible densification."

**4. Build a full-process quality management and standard certification platform**

Promote the inclusion of high-end tungsten alloy tube materials in aviation/medical system standards such as AS9100 and ISO13485, establish product traceability and process control data chains, build a service test experimental platform (such as high-temperature thermal cycles, neutron irradiation, corrosion fatigue and other composite simulations), and enhance product international certification and application access capabilities.

**5. Expand high-value application markets and drive demand-driven innovation**

Targeting national strategic projects and emerging high-end fields, such as nuclear fusion projects, space probe heat flow tubes, particle accelerator channels, electronic chip heat dissipation tubes, etc., we carry out customized development of tungsten alloy tubes and collaborative design of composite applications, and promote the transformation from "material products" to "application solutions".

### III. Conclusion

The tungsten alloy tube industry not only represents high-tech in tungsten deep processing but also represents a significant reflection of China's high-end manufacturing capabilities. Future industrial upgrades will no longer be limited to the production of "denser and more durable" materials, but will instead encompass breakthroughs across the entire supply chain, centered on system collaboration, process intelligence, and application integration. If leading companies like CTIA GROUP can continue to focus on advanced alloy systems, intelligent fabrication technologies, and

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a voice in international standards, they will secure a core competitive position in the global tungsten alloy tube industry .

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电话/TEL: 0086 592 512 9696  
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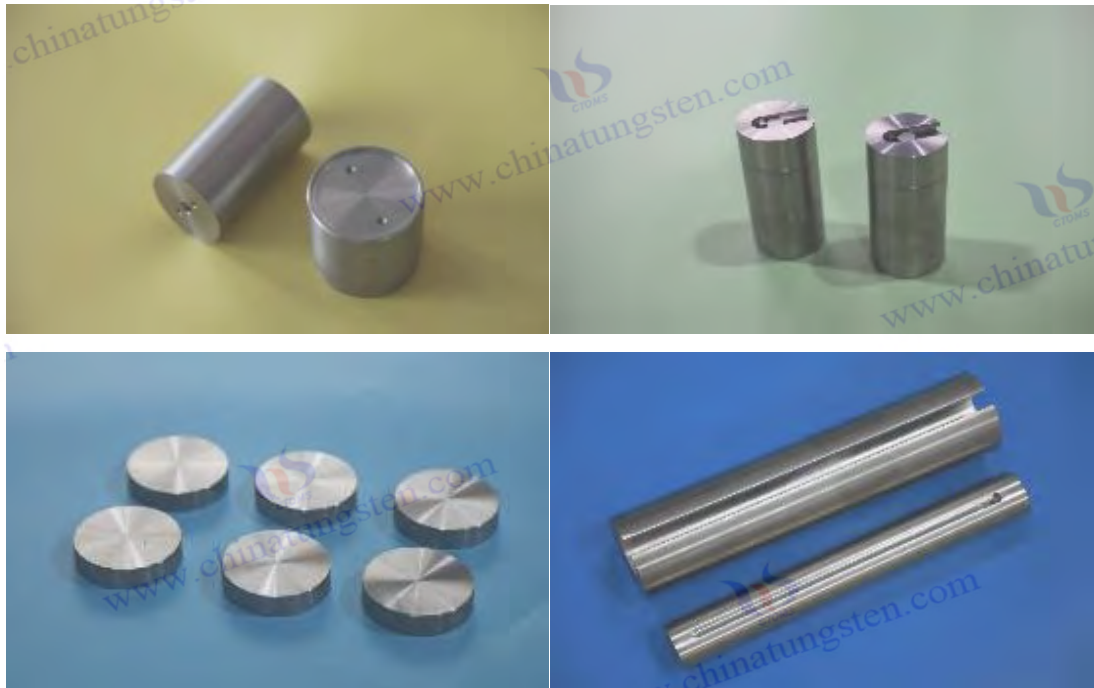
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电话/TEL: 0086 592 512 9696  
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## Chapter 10 Research Frontiers and Future Development of Tungsten Alloy Tubes

### 10.1 Research on High Densification and Complex Shape Forming of Tungsten Alloy Tubes

Tungsten alloy tubes, due to their excellent physical and mechanical properties, hold an irreplaceable strategic position in fields such as nuclear energy, aviation, medicine, and electronics. However, to meet increasingly stringent operating environments and design requirements, controlling their structural density and geometric form has become a key technical bottleneck. With the growing demand for high-density tungsten alloy tubes and complex structural components, research institutions and companies at home and abroad are continuously conducting in-depth research on their forming mechanisms, densification processes, and innovative manufacturing techniques, driving the material's evolution from traditional homogeneous tubes to functionalized, structurally integrated, and multi-scale complex forms.

#### 1. The significance of high-density tungsten alloy tubes

tungsten alloy tubes directly affects their shielding effectiveness, mechanical strength, and service life. Under conditions such as high-energy radiation, high pressure differentials, and high heat flux, porosity or localized loose areas can easily lead to thermal instability, strength degradation, and even structural failure. Therefore, increasing material density ( $\geq 99.5\%$  of theoretical density) is not only a prerequisite for ensuring product performance but also a fundamental requirement for achieving high-end applications in multiple fields.

#### 2. Main Directions and Core Technologies of High Densification Research

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## 1. Ultrafine powder preparation and spherical modification

The prerequisites for dense forming are high fluidity and uniform composition. Current research focuses on:

- Co-spheroidizing treatment of **nano-submicron tungsten powder and alloying element (Ni, Fe, Cu, etc.) powder**;
- Plasma spheroidization, spray drying-reduction route to improve powder filling density and compressibility;
- Particle size distribution and surfactant design to optimize initial forming state.

## 2. High uniformity pressing technology

Molding and cold isostatic pressing (CIP) are traditional processes. The latest research attempts:

- **Warm pressing** or hot isostatic initial pressing (THIP) increases density while improving micropore sealing efficiency;
- Finite element simulation is used to optimize mold cavity design and pressing path, and to control wall thickness distribution and coaxiality;
- **multi-axis rotary pressing** technology to improve the volume density and shape accuracy of cylindrical pipes.

## 3. Densification sintering technology

The sintering process is a key stage for pore closure and grain connection:

- Adopt **vacuum-hydrogen multi-stage sintering** and **transition atmosphere control technology** to achieve low porosity residue;
- Study the control of liquid phase distribution in tungsten alloy to improve the uniform penetration and wetting of low melting point phases such as Ni/Fe in tubular sintered parts;
- Slight additions of Mo, Re, Ti and other elements optimize the liquid phase sintering path and grain boundary migration ability.

## 4. Auxiliary densification path

- **\*\*Hot isostatic pressing (HIP)\*\*** is particularly effective in sealing residual pores inside pipes. Research focuses on optimizing the hot pressing pressure-temperature-holding time window.
- Rapid sintering methods such as **plasma densification , microwave sintering, and spark plasma sintering (SPS)** have become the research frontier for the manufacture of dense tungsten alloy tubes;
- **Cold-hot synergistic heat treatment** (such as rapid retreat-repressurization method) is gradually used in the manufacture of thick-walled, high-density pipes.

## 3. Exploration of forming technology for complex tungsten alloy tubes

tungsten alloy has high traditional machining costs and poor forming freedom, especially in complex geometric structures such as thin walls, bends, internal spirals, and special-shaped channels. Forming capability has become a research and development focus.

### 1. Powder Injection Molding (PIM) Technology

Suitable for small diameter, thin wall and complex tungsten alloy tubes:

- It can produce microstructure components such as spiral grooved tubes, splitters, and jacketed channel tubes;

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- Study the filling uniformity and degreasing path of injection molds to prevent cracking and falling off.

## 2. Additive Manufacturing (AM) and Tubular Structure Printing

Laser directed energy deposition (DED), electron beam melting (EBM), etc. are suitable for tungsten alloys:

- It can realize the forming of **multi-layer spiral casing structure** and **gradient wall thickness structure** ;
- The current difficulties lie in crack control, pore formation, thermal stress accumulation and alloy composition segregation.

## 3. Liquid metal centrifugal casting and cold spray internal coating method

Explore the integrated casting of hollow pipes and the composite forming of inner wall functional coatings to improve the structural and functional integration;

- Centrifugal casting can be used for the initial production of thick-walled tungsten alloy tubes;
- Cold spray technology is combined with tungsten powder and Cu/Ni composite powder to prepare the inner conductive and thermal conductive layer.

## 4. Integrated Simulation and Intelligent Forming

In order to control the forming quality and optimize the structural design, **a multi-physics simulation model of tungsten alloy tube is established** :

- Combine rheological forming behavior, heat conduction behavior and phase field evolution simulation;
- Introducing machine learning to assist in optimizing pressing process parameters and predicting defects;
- For special-shaped pipe fittings, **the additive-subtractive collaborative manufacturing path planning** and deformation compensation mechanism are studied.

## V. Conclusion

Research on high densification and complex shape forming of tungsten alloy tubes is not only an important technological frontier in the field of materials processing, but also a core path to meet future extreme application needs and realize high-value applications of tungsten alloy materials. Future development will focus on:

- Fine powder design and intelligent pressing path control;
- Integration of multi-scale sintering densification mechanisms and heat treatment pathways;
- additive manufacturing and integrated forming processes for composite structures;
- Improve manufacturing intelligence based on simulation and data-driven.

Breakthroughs in this direction are expected to greatly promote the structural innovation and functional integration of tungsten alloy tubes in key fields such as aerospace, nuclear energy, military industry, and high-end medical care, and open up a new era in the manufacturing of new high-performance metal structural parts.

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## Additive Manufacturing Integration and Intelligent Manufacturing of Tungsten Alloy Tubes

Tungsten alloy tubes, an advanced material combining high density, high melting point, high strength, and excellent corrosion resistance, are seeing their applications expand beyond traditional nuclear and military applications to emerging high-end sectors such as aerospace, medical equipment, electronic protection, and energy systems. These applications not only place higher demands on the performance of tungsten alloy tubes but also present new challenges in forming complexity, manufacturing efficiency, and product consistency. Traditional powder metallurgy and machining methods have demonstrated limitations in achieving complex geometries, improving material utilization, and shortening R&D cycles. Therefore, the integrated application of **additive manufacturing (AM) and intelligent manufacturing technologies is becoming a key direction for technological innovation in tungsten alloy tube production**.

### 1. Advantages and significance of additive manufacturing of tungsten alloy tubes

with traditional cutting or molding + sintering processes, the core advantages of additive manufacturing in the preparation of tungsten alloy tubes are reflected in the following aspects:

- **Strong ability to form complex structures** : It can directly prepare special-shaped hollow structures with spiral inner grooves, variable diameter sections, composite channels, etc., and realize the design of tungsten alloy tube structures that are difficult to process with traditional processes.
- **Save materials and energy consumption** : reduce material waste, especially suitable for the efficient utilization of high-cost metal resources such as tungsten.
- **Personalization and rapid manufacturing** : The size, wall thickness, and structure of tungsten alloy tubes can be quickly customized according to the end-use scenario, reducing mold dependence.
- **Refined control of microstructure** : By controlling the quenching rate, deposition path, etc. through process parameters, multi-scale microstructure gradient design and enhancement can be achieved.

### 2. Main technical routes of additive manufacturing of tungsten alloy tubes

#### 1. Selective Laser Melting (SLM)/Electron Beam Melting (EBM)

- Suitable for manufacturing small size, high precision thin wall tungsten alloy tube components.
- It can achieve hollow structural parts with a powder layer thickness of 20–50  $\mu\text{m}$  and a printing accuracy of  $\pm 0.05\text{ mm}$ .
- However, due to the high thermal conductivity and extremely high melting point of tungsten alloy ( $>3400^{\circ}\text{C}$ ), it needs to be operated on a **high-temperature preheating platform, in an inert atmosphere or in a vacuum environment** to reduce cracks and residual stress.

#### 2. Directed Energy Deposition (DED)/Laser Cladding

- Suitable for medium and large size tungsten alloy tube billets or local structure repair.

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- Metal powder/ wire can be deposited layer by layer using laser or electron beam **to form a near-net-size hollow cylinder** .
- It has the advantages of high preparation efficiency, high material utilization rate and strong adaptability, and has been used in the manufacture of some military and aerospace composite casing structures.

### 3. Cold Spray + Post-processing

- Tungsten alloy powder is deposited on the substrate by high-speed carrier gas to form a tubular structure, which is suitable for preparing the inner layer or functional layer of **tungsten alloy composite tubes** .
- Subsequent heat treatment or HIP can further improve density and bonding strength.
- Cold spraying is particularly suitable for the preparation of the middle layer of **tungsten-copper and tungsten-nickel composite pipes** , and has the advantages of small heat-affected zone and low residual stress.

### 4. Composite additive + subtractive collaborative manufacturing

- Combining additive manufacturing with CNC machining (such as inner hole boring and outer wall grinding) can achieve **high-precision and high-density pipe preparation** .
- **hybrid process chain** of “additive forming + CNC trimming + HIP densification” can be used to achieve stable batch manufacturing.

## 3. Key Technology Paths for Intelligent Manufacturing of Tungsten Alloy Tubes

With the improvement of digitalization and intelligentization of manufacturing technology, tungsten alloy tube production is gradually integrating into the " **Industry 4.0** " paradigm. Its intelligent manufacturing development directions mainly include:

### 1. Multi-source process data collection and real-time feedback

- **Real-time temperature, power, and deformation monitoring** of the deposition process is achieved through high-temperature cameras, optical monitors, and heat flow sensors ;
- Identify material defects such as ablation, holes, cracks, etc. in real time and provide feedback to adjust parameters.

### 2. Process modeling and intelligent process optimization

- Establish a **simulation model of the molten pool behavior of tungsten alloy powder** under high-energy beam ;
- Use artificial intelligence algorithms (e.g., neural networks, Bayesian optimization) to predict optimal paths, energy density, and scanning speeds;
- Realize automatic printing path planning and failure prediction.

### 3. Digital Twin and Closed-Loop Control System Construction

- Through 3D digital modeling and real-time mapping of printing status, a **virtual-real fusion system for additive manufacturing of tungsten alloy tubes is constructed** ;
- It realizes functions such as **defect prediction, performance simulation, and process backtracking** to provide guarantees for quality consistency control.

### 4. Flexible manufacturing units and intelligent production line construction

- intelligent additive manufacturing unit with "self-identification, self-correction, and self-adjustment" capabilities ;

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- Realize the full process automation closed loop of tungsten alloy tube from **powder feeding, additive forming , heat treatment to testing and packaging .**

#### IV. Development Challenges and Future Prospects

Although additive manufacturing and intelligent manufacturing bring great potential to the preparation of tungsten alloy tubes, there are still many challenges in the promotion of industrialization:

- **Insufficient powder adaptability** : The preparation of spherical and high-purity tungsten alloy powder is difficult and costly.
- **Cracks and pores are difficult to control** : the high melting point leads to uneven cooling, which easily forms defects, and requires optimization of energy density and deposition strategy.
- **High equipment specialization requirements** : The printing system needs to adapt to high-temperature and high-density metal deposition, and the hardware investment cost is high.
- **The standards and evaluation system are not yet perfect** : in particular, the structural strength and fatigue life assessment standards for special-shaped tungsten alloy pipes need to be established.

In the future, we should promote tungsten alloy tubes from "laboratory additive manufacturing" to "large-scale intelligent manufacturing" through integrated design of materials, processes and structures , data-driven optimization and improvement of the standard system to meet the urgent needs of the country's high-end manufacturing and strategic emerging industries.

#### In summary, the integration

of additive manufacturing and intelligent manufacturing for tungsten alloy tubes will significantly enhance their adaptability to structural complexity , manufacturing flexibility, and performance consistency, becoming a core development direction for the next generation of high-performance tungsten-based tube fittings . As the technology matures and its applications expand, it is expected that within the next five years, an advanced tungsten alloy tube manufacturing system featuring multi-technical integration, industry chain collaboration, and standardized support will be established, helping China achieve independent control of key materials in fields such as aerospace, nuclear energy, and strategic defense.

#### 10.3 Integrated Development and Application Expansion of Multifunctional Tungsten Alloy Composite Tubes

tungsten alloy composite tubes are gaining increasing attention in the high-end manufacturing sector. Compared to traditional single-material tungsten alloy tubes, multifunctional tungsten alloy composite tubes offer superior advantages in terms of material composition, mechanical structure, functional integration, and service performance. Their development goals are not only to maintain the fundamental properties of tungsten alloy, such as high specific gravity, high melting point, and

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high strength, but also to incorporate functional modules such as thermal conductivity, anti-magnetism, electromagnetic shielding, corrosion resistance, and wear resistance through a composite design to meet the diverse needs of complex service environments.

1. Basic design concept of multifunctional tungsten alloy composite tube

1. Structure-function synergy principle

composite tungsten alloy tubes is no longer limited to mechanical load support, but emphasizes the **integration of structure and function** . For example, the outer layer has high hardness and corrosion resistance for protection, the middle layer optimizes thermal conductivity or anti-magnetic properties, and the inner layer achieves electrical signal conduction or biocompatibility.

2. Material gradient and interface design

By using **\*\*functionally graded materials (FGMs)\*\*** or multilayer composite structures, the thermal expansion matching and stress transition between different metals (such as tungsten-copper, tungsten-nickel-iron, tungsten- molybdenum , etc.) are optimized to reduce the risk of interface delamination and crack propagation.

3. Synergistic optimization of ingredients and performance

Taking into account the requirements of the pipe's thermal conductivity, electrical properties, magnetic response, corrosion resistance, etc., **composite material design, microalloying regulation, nanoparticle dispersion strengthening** and other means are adopted to achieve a synergistic improvement in performance.

2. Typical multifunctional tungsten alloy composite tube structure types

Structure Type	Features	Typical uses
Coaxial multi-layer composite tube (such as W-Cu-W)	Internal heat conduction, external protection	High-frequency power supply heat dissipation, spacecraft thermal control system
Gradient functional tube (such as W→W-Ni→W-Cu )	Resistant to thermal shock and good structural strength	Missile tail compartment casing, reactor control components
Metal-ceramic composite tubes (such as W- ZrO <sub>2</sub> )	High temperature anti-oxidation, anti-radiation	Plasma vessels, accelerator components
Multi-core channel composite tube (such as W-Cu core + W-Ni shell)	Multifunctional conduction, electromagnetic shielding	Medical equipment, particle beam delivery devices
Surface coating composite tube (such as W tube + TiN coating)	Wear and corrosion resistant	High-speed mechanical transmission, wear-resistant conduit

3. Key preparation and forming technologies

1. Powder metallurgy composite pressing

through **layered filling or segmented pre-pressing** , and good interface bonding is achieved through hot pressing and sintering.

2. Coaxial extrusion

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Applicable to core-shell structure tungsten alloy composite tubes, ensuring synchronous deformation and plastic matching of the interface of multiple materials during forming.

### 3. Cold spraying and laser cladding

Used to add functional coatings (such as radiation-resistant ceramics, conductive alloys, etc.) to the outside or inner wall of the tube to achieve **local strengthening and surface function integration**.

### 4. Additive Manufacturing

The integrated forming of complex functional composite tubes can be achieved through **multi-material 3D printing platforms** (such as dual-powder path SLM or DED), which has great design freedom.

### 5. Hot isostatic pressing (HIP) densification treatment

Improving interface bonding strength and overall density is a key step in the mass production of tungsten alloy composite tubes.

## 4. Typical Applications and Expansion of Multifunctional Tungsten Alloy Composite Tubes

### 1. Nuclear energy and fusion devices

- Used for **neutron shielding guide tubes, control rod sleeves, and cooling circuit protective tubes** ;
- The composite design can significantly improve the thermal shock resistance and radiation resistance;
- W-Cu-ZrO<sub>2</sub> type composite structures are widely used in nuclear thermal engineering conduits.

### 2. Aerospace systems

- Used for **high temperature engine guide tubes, aircraft counterweights and shielding ducts** ;
- W-Ni-Cu tubes provide high strength and good thermal management performance;
- inner core thermal conductive material + outer layer high strength tungsten alloy has become a trend.

### 3. Military and ballistic protection

- Applied to **high-penetration ammunition guide tubes, inertial navigation components, and bulletproof casings** ;
- The tungsten-molybdenum-nickel-iron composite structure has excellent toughness and impact resistance.

### 4. Medical devices and radiation protection

- Manufacturing of **gamma ray/X-ray therapy positioning tubes and particle beam channels** ;
- A tungsten-copper composite inner layer is used to improve thermal management and diffuse energy absorption.

### 5. Advanced electronics and quantum devices

- Used in **microwave ducts, shielding covers, and anti-magnetic core tube structures** ;
- The composite thermal conductive and anti-magnetic structure can improve stability and anti-interference capabilities.

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## V. Future Technology Trends and Challenges

### 1. Precise interface control

composite pipes lies in the **interface bonding quality between different materials**. In the future, in-depth research is needed on element diffusion, interface phase change, and residual stress control mechanisms.

### 2. Multifunctional integrated design tool

Develop a **multi-physics field simulation platform** to realize the integrated evaluation and structural optimization of the mechanical, thermal, magnetic and radiation behaviors of composite pipes.

### 3. Improved forming capability of large special-shaped composite pipes

It is necessary to develop **high-throughput additive manufacturing systems and high-precision core shaft mold systems** to meet the needs of large-scale and complex structures.

### 4. High-throughput performance evaluation and standard establishment

Currently, there is a lack of systematic testing and service evaluation standards for multifunctional composite tungsten alloy tubes, which restricts their popularization in high-demand industries such as nuclear energy and military industry.

## Conclusion: The integrated development of

multifunctional tungsten alloy composite tubes represents a fundamental shift in tungsten alloy material applications from "single structural materials" to "high-performance, multi-field coupled functional materials." Its technology encompasses a multidisciplinary intersection, encompassing material design, composite forming, interface control, and multi-performance evaluation. It is a strategic key to the deep penetration of tungsten materials into high-end manufacturing systems. With the advancement of technological platforms, manufacturing capabilities, and standards, tungsten alloy composite tubes will play an irreplaceable role in core industries such as nuclear energy, aerospace, quantum information, and precision medicine.

## 10.4 Performance Evolution of Tungsten Alloy Tubes in Extreme Service Environments

As a key material with high specific gravity and strength, tungsten alloy tubes are widely used in a variety of extreme service environments, including aerospace, nuclear energy, military, and medical applications. These extreme environments typically involve complex conditions such as high temperature, high pressure, high radiation, severe corrosion, and mechanical stress. The performance evolution of tungsten alloy tubes in such environments not only impacts their structural safety and service life, but also directly influences the reliability and stability of the overall system. The following analysis examines the performance evolution mechanisms and mitigation strategies for tungsten alloy tubes based on key extreme service factors.

### 1. Performance evolution in high temperature environment

#### 1. Thermal expansion and thermal fatigue

Tungsten alloy tubes experience thermal expansion at high temperatures. This differential expansion between tungsten (which has a lower thermal expansion coefficient) and the metal binder phase (such as nickel, iron, and copper) leads to internal thermal stress. Long-term thermal cycling can

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trigger the initiation and propagation of microcracks, leading to thermal fatigue failure. At the microscopic level, this leads to grain coarsening and increased interfacial diffusion, reducing the material's strength and density.

## **2. High temperature oxidation and corrosion**

Tungsten oxidizes at high temperatures in air or oxygen-containing environments to form oxides such as  $WO_3$ , which can lead to surface embrittlement and quality loss. Other alloy components (nickel and iron) can also accelerate the oxidative corrosion process. The newly exposed surface after the oxide layer peels off accelerates corrosion, reducing the overall durability of the pipe.

## **3. Crystal structure stability**

At high temperatures, the crystal structure of tungsten alloys undergoes phase transformation or dissolution of precipitation-strengthening phases, affecting hardness and toughness. Some strengthening phases have poor high-temperature stability, leading to a decrease in the overall mechanical properties of the alloy.

## **2. Performance Evolution in High Radiation Environments**

### **1. Irradiation-induced point defects and dislocations**

In radiation environments such as those in nuclear reactors, high-energy neutrons or gamma rays can induce lattice defects, vacancies, and interstitial atoms, leading to crystal distortion and affecting the alloy's plasticity and toughness. Radiation hardening also makes the material brittle, increasing the risk of fracture.

### **2. Irradiation-induced phase transformation and precipitation**

Radiation energy may also induce phase transformation, precipitation or agglomeration of the second phase in the alloy, changing the material microstructure and further affecting the mechanical properties and corrosion behavior.

### **3. High mechanical load and impact conditions**

Tungsten alloy tubes are often subjected to impact, vibration, and cyclic loading during service. Despite their significant advantages in density and strength, long-term mechanical fatigue can still lead to crack propagation and fatigue fracture. Microcracks propagate along grain boundaries, especially under the combined effects of high temperature and radiation.

### **4. Impact of strong corrosive environment**

In acidic, alkaline, or chloride-containing corrosive media, microscopic corrosion pits may form on the surface of tungsten alloy tubes, increasing surface roughness, localized stress concentration, and accelerating fatigue crack formation. The electrochemical activity of components such as nickel and iron in the alloy has a significant impact on the overall corrosion resistance.

## **5. Comprehensive Mechanism and Prediction of Performance Degradation**

tungsten alloy tubes is the result of the coupling effect of the above factors, presenting a nonlinear and complex dynamic process. Typical mechanisms include:

- Crack initiation and growth induced by thermal-mechanical coupled stress;
- Microstructural evolution induced synergistically by irradiation and heat;

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- Effects of surface oxide layer and corrosion product formation on mechanical properties;
- The internal defects of the material accumulate and the fracture toughness decreases.

Mechanism-based multi-physics simulation has become an important tool for predicting the evolution of service performance and life assessment of tungsten alloy tubes.

## 6. Response Strategies and Material Optimization Directions

In order to improve the performance stability of tungsten alloy tubes in extreme environments, the following measures are usually taken:

- Design high thermal stability alloy composition to inhibit grain coarsening and strengthening phase dissolution;
- Surface coating technology (ceramic coating, anti-oxidation film) to prevent oxidation corrosion;
- Microalloying and nanostructure strengthening to improve radiation resistance and mechanical toughness;
- Optimize heat treatment process and adjust residual stress distribution;
- Develop high-temperature and radiation-resistant composite tungsten alloy tubes to achieve multi-level protection.

## VII. Summary

tungsten alloy tubes under extreme service environments exhibits high complexity and variability. A comprehensive understanding of the multi-field coupling effects of heat, radiation, mechanical forces, and chemical reactions is key to optimizing material design and ensuring safe service. In the future, the integration of advanced material design concepts and intelligent simulation technologies will drive the development of tungsten alloy tubes towards higher performance, longer lifespans, and a wider range of applications, meeting the demanding requirements of aerospace, nuclear energy, and high-end industrial sectors.

## 10.5 Sustainable Development Strategy and Alternative Materials Research for Tungsten Alloy Tubes

With the increasing global emphasis on sustainable resource utilization and environmental protection, the sustainable development of tungsten alloy tubes, as important high-performance materials, has become a key focus of industry attention. The limited nature of tungsten resources, the environmental impact of mining, and the energy consumption and waste disposal issues associated with the manufacturing and recycling of tungsten alloy tubes have prompted industry and research institutions to actively explore green manufacturing pathways, recycling systems, and alternative material development for tungsten alloy tubes. The following article details sustainable development strategies for tungsten alloy tubes and the current status of research into alternative materials.

### 1. Tungsten Alloy Tube Resource Utilization and Circular Economy Strategy

#### 1. Optimization and efficient utilization of raw materials

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Tungsten ore resources are concentrated and limited in reserves. Efficient utilization of tungsten raw materials is fundamental to the sustainable development of tungsten alloy tubes. By optimizing the powder preparation process, increasing alloy density, and reducing processing losses, we can maximize raw material utilization. Using high-purity, low-impurity tungsten powder helps improve alloy performance and reduce subsequent processing difficulties.

#### **Recycling and reuse of waste tungsten alloy tubes**

We have established a comprehensive tungsten alloy tube recycling system, recovering tungsten from waste materials through physical and chemical methods to achieve resource recycling. The recycling process includes mechanical crushing, pulverization, chemical leaching, and refining to ensure the quality of the recovered tungsten powder meets the requirements of secondary processing. We also develop green recycling technologies to reduce harmful emissions and improve recycling efficiency.

### **3. Energy saving and consumption reduction in the manufacturing process**

During the production of tungsten alloy tubes, low-energy forming and sintering processes, such as high-frequency induction heating, plasma-assisted sintering, and additive manufacturing, are used to reduce energy consumption and carbon emissions. At the same time, production processes are optimized to reduce waste and promote green manufacturing.

## **2. Environmental Impact and Green Manufacturing of Tungsten Alloy Tubes**

### **1. Environmental risk assessment**

The mining and processing of tungsten and its alloys may generate heavy metal pollution, necessitating a scientific assessment of environmental risks. We must strengthen the treatment of wastewater and exhaust gas to prevent the leakage of hazardous substances and ensure compliance with environmental regulations.

### **2. Promotion of green manufacturing technology**

Promote harmless, low-emission manufacturing technologies, such as water-based dispersion systems, environmentally friendly additives, and lead-free soldering processes, to reduce environmental impact. Tungsten alloy tube manufacturers should actively participate in environmental management system certification (such as ISO 14001) to promote sustainable development.

## **3. Research and Development Progress of Tungsten Alloy Tube Alternative Materials**

### **1. Lightweight and high-strength metal materials**

To meet the demand for lightweighting, aluminum- and magnesium-based high-strength alloys and high-entropy alloys are being studied as potential alternatives to tungsten alloy tubes. Although these materials have lower densities, through alloy design and surface strengthening, they have the potential to replace tungsten alloy tubes in specific applications and reduce the overall structural weight.

### **2. High-density alloys and composite materials**

Tungsten-molybdenum-based alloys, tungsten-tantalum alloys, and tungsten-based intermetallic compound composites exhibit excellent high-temperature performance and radiation resistance, making them an important alternative to tungsten alloy tubes. Composite materials, such as tungsten

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alloy reinforced with ceramics or carbides, enhance wear and corrosion resistance while maintaining high density.

### 3. Additive Manufacturing of Functionally Graded Materials

By using additive manufacturing technology to achieve functional gradients and multi-material composite structures, we are developing tungsten alloy tube alternatives optimized for specific working conditions. This technology can significantly improve material utilization, reduce costs, and achieve lightweight design.

## IV. Policies and Industry Promotion Measures

### 1. Policy support and regulations

The government and industry associations have formulated policies for tungsten resource management and recycling, encouraging green manufacturing and the development of a circular economy. Special funds have been established to support the research and development of sustainable technologies for tungsten alloy tubes, promoting the improvement of standards systems and environmental regulations.

### 2. Corporate Responsibility and Social Engagement

Tungsten alloy tube manufacturers should assume environmental protection responsibilities, establish and improve environmental management systems, and actively participate in the recycling and reuse of waste materials. Through technological innovation, they can reduce environmental burdens and achieve a win-win situation in terms of economic and environmental benefits.

## V. Future Outlook

tungsten alloy tubes requires a balanced approach to resource conservation, environmental protection, and industrial upgrading. Future research should be strengthened to promote innovation in green manufacturing technologies and efficient recycling processes, develop high-performance alternative materials, and enhance the competitiveness of tungsten alloy tubes in high-end applications. By combining intelligent manufacturing with digital management, a green closed-loop system for the entire life cycle of tungsten alloy tubes can be achieved , helping the materials industry move towards a new era of green, low-carbon, and sustainable development.

In summary, the sustainable development strategy for tungsten alloy tubes encompasses efficient resource utilization, green manufacturing, waste recycling, and the development of alternative materials. This strategy is crucial for ensuring long-term stable supply and environmental compliance . Through policy guidance, technological innovation, and industry collaboration, the tungsten alloy tube industry will steadily advance toward high quality and low environmental impact.

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## Appendix

### Appendix 1 : Common physical/mechanical properties of tungsten alloy tubes

Performance Category	Specific indicators	Typical value range	Remarks
Physical properties	Density (g/cm <sup>3</sup> )	17.0 – 18.8	by alloy composition and density
	proportion	17.0 – 18.8	the tungsten content, the greater the specific gravity
	Linear expansion coefficient (×10 <sup>-6</sup> / K)	4.5 – 6.5	Suitable for high temperature environments
	Thermal conductivity (W/m·K)	100 – 150	Variation with alloy ratio
	Resistivity (μΩ·cm)	0.2 – 0.5	Affects electrical performance
Mechanical properties	Tensile strength (MPa)	500 – 900	Related to composition and heat treatment process
	Yield strength (MPa)	300 – 700	
	Elongation (%)	1 – 10	Generally low, belongs to cemented carbide
	Hardness (HV)	250 – 400	Varies according to ingredients and processing status
	Impact toughness (J/cm <sup>2</sup> )	5 – 20	Affected by microstructure
Other performance	Corrosion resistance	good	Depends on alloy composition and surface treatment
	Radiation resistance	excellent	Used in special environments such as nuclear energy

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

Brand	Tungsten (W) wt. %	Nickel (Ni) wt. %	Iron (Fe) wt. %	Copper (Cu) wt. %	Other element content	Main uses and characteristics
WNiFe-90	90	7.0	3.0	—	Trace impurities	High density, excellent mechanical properties, often used in military and aviation counterweights
WNiFe-92	92	6.0	2.0	—	Trace impurities	High strength, high density, suitable for precision instruments
WNiFe-95	95	4.5	0.5	—	Trace impurities	Very high density, good anti-wear performance, nuclear industry application

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WNiCu-85	85	—	—	15	Trace impurities	Good thermal conductivity and mechanical properties, electronic cooling devices
WNiCu-90	90	—	—	10	Trace impurities	High-density tungsten-copper alloy with excellent mechanical strength
WNiCu-95	95	—	—	5	Trace impurities	Suitable for high temperature environment and high density requirements

illustrate:

- The element contents in the table are typical design values. Actual production may vary slightly due to formula and process.
- The brand name is generally named after the main alloying element and tungsten content to facilitate the distinction between different performance grades.
- The "trace impurities" in the brand usually include sulfur, phosphorus, oxygen, carbon, etc., which have a certain impact on performance and need to be strictly controlled.
- The brand should be selected based on the specific application environment and performance requirements.

### Appendix 3: Compilation of relevant standard documents and technical data on tungsten alloy tubes

#### 1. National and industry standards

- GB/T 14248-2011 Technical Requirements for Tungsten Alloy Materials
- YS/T 264-2004 Heavy Tungsten Alloys
- GB/T 18254-2000 Technical Specifications for Tungsten Alloy Tubes
- HG/T 2041-2006 Test Methods for Tungsten Alloy Material Properties
- GB/T 228.1-2010 "Tension test of metallic materials - Part 1: Room temperature test method"

#### 2. International Standards

- ASTM B777-18 Standard Specification for High-Density Tungsten Alloy Rods and Tubes
- ISO 9001:2015 Quality Management System Requirements
- ISO 14001:2015 Environmental Management System Requirements
- MIL-DTL-46027B Technical Specifications for Military Tungsten Alloy Materials
- ISO 6507-1 Hardness test methods - Vickers hardness test

#### 3. Tungsten Alloy Tube Related Technical Literature

- Tungsten Alloy Material Handbook, China Nonferrous Metals Industry Press, 2018
- "Research on Preparation Technology and Properties of Tungsten Alloy", Wang Qiang, Materials Review, Issue 6, 2020
- "Analysis of the Application of Tungsten Alloy Tubes in the Nuclear Industry," Li Ming, Nuclear Technology, Issue 5, 2019

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- "Discussion on Heat Treatment Technology of High-Performance Tungsten Alloy Tubes," by Zhang Hua, Metal Heat Treatment, Issue 3, 2021
- "Nondestructive Testing Technology of Tungsten Alloy Tubes," by Chen Gang, Nondestructive Testing, Issue 7, 2019

#### 4. Patent information

- CN109876543A Preparation method and application of tungsten alloy tube
- CN110234567B High-performance tungsten alloy tube and its manufacturing process
- US102345678B2 Tungsten alloy tube with enhanced mechanical properties

#### 5. Industry reports and market analysis

- Global Tungsten Alloy Industry Development Report, China Tungsten Industry Association, 2023
- Tungsten Alloy Tube Market Demand and Future Trend Analysis, CCID Consulting, 2024
- Tungsten Alloy Material Technology Innovation White Paper, CTIA GROUP Research Center, 2023

#### 6. Technical standards and test method guidance

- Tungsten Alloy Material Mechanical Properties Testing Procedure, National Center for Materials Testing, 2022
- Technical Specifications for Size and Shape Testing of Tungsten Alloy Tubes, China Machinery Industry Standardization Research Institute, 2021
- Guidelines for Nondestructive Testing of Surface Defects in Tungsten Alloy Tubes, Society for Nondestructive Testing, 2023

#### 7. Academic papers and conference materials

- Proceedings of the International Conference on Tungsten and Refractory Metals, 2022
- Journal of Materials Science & Technology — Special Issue on Tungsten Alloys, 2023
- "Research on Performance Optimization and Application of High-density Tungsten Alloy Tubes", Proceedings of the Annual Conference of the Chinese Society for Materials Research, 2023

### Appendix 4: Tungsten Alloy Tube Glossary and English Abbreviations

#### 1. Tungsten Alloy Tube Related Terms

- **Tungsten Alloy Tube is a hollow tube made**  
of high-density tungsten and alloy elements through powder metallurgy and forming processes. It has high density, high strength and good corrosion resistance.
- **Powder metallurgy (PM)**  
is a method of preparing alloy materials by pressing and sintering metal powders, which is suitable for preparing high-density tungsten alloy tubes.

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- **Isostatic Pressing (HIP)**  
is a compacting method that applies uniform pressure to a powder body, which helps to improve the density and uniformity of the material.
- **Sintering**  
is a process of heating a powder body to combine its particles into a solid material, which is key to the formation of tungsten alloy tube performance.
- **Densification**  
refers to the process of reducing the internal pores of the material and increasing the density, which directly affects the mechanical properties of tungsten alloy tubes.
- **Microstructure**  
refers to the structural morphology inside the material visible under a microscope, including grain size, phase distribution, etc., which affects performance.
- **Mechanical properties**  
include mechanical performance indicators of materials such as strength, hardness, toughness, and elastic modulus.
- **Non-destructive testing (NDT)**  
is a method of evaluating internal or surface defects of materials without destroying the materials, such as ultrasonic and radiographic testing.
- **Corrosion Resistance:**  
The ability of a material to resist chemical or electrochemical corrosion.
- **Additive Manufacturing (AM) is**  
an advanced manufacturing technology that manufactures complex-shaped workpieces by stacking materials layer by layer.
- **Surface treatment is**  
a process to improve the surface properties of materials, including polishing, electroplating, spraying, etc.
- **Wall Thickness Uniformity**  
refers to the consistency of the tungsten alloy tube wall thickness in the length and circumference.
- **Concentricity**  
is the degree of coincidence of the axes of the inner and outer cylindrical surfaces.

## 2. Explanation of English abbreviations

Abbreviations	Full name	Interpretation
PM	Powder Metallurgy	Powder Metallurgy
HIP	Hot Isostatic Pressing	Hot isostatic pressing
NDT	Non-Destructive Testing	Nondestructive Testing
SEM	Scanning Electron Microscope	Scanning electron microscopy
XRD	X-ray Diffraction	X-ray diffraction
ICP	Inductively Coupled Plasma	Inductively coupled plasma optical emission spectroscopy for elemental analysis

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<b>XRF</b>	X-ray Fluorescence	X-ray fluorescence analysis
<b>ONH</b>	Oxygen, Nitrogen, Hydrogen Analysis	Oxygen, nitrogen and hydrogen content analysis
<b>ASTM</b>	American Society for Testing and Materials	American Society for Testing and Materials
<b>GB/T</b>	Guóbiāo (National Standard, Recommended)	China National Recommended Standard
<b>YS/T</b>	Industry Standard	Industry Standards
<b>RoHS</b>	Restriction of Hazardous Substances	Restriction of the use of certain hazardous substances
<b>REACH</b>	Registration, Evaluation, Authorization and Restriction of Chemicals	Registration, Evaluation, Authorisation and Restriction of Chemicals (RECs)
<b>MSDS</b>	Material Safety Data Sheet	Material Safety Data Sheets
<b>PVD</b>	Physical Vapor Deposition	Physical Vapor Deposition
<b>AM</b>	Additive Manufacturing	Additive Manufacturing
<b>ISO</b>	International Organization for Standardization	International Organization for Standardization
<b>MIL</b>	Military Standard	Military Standard

The above terms and abbreviations are intended to help readers quickly understand the commonly used professional terms and related standard expressions in the field of tungsten alloy tubes , and facilitate technical exchanges and literature reading.

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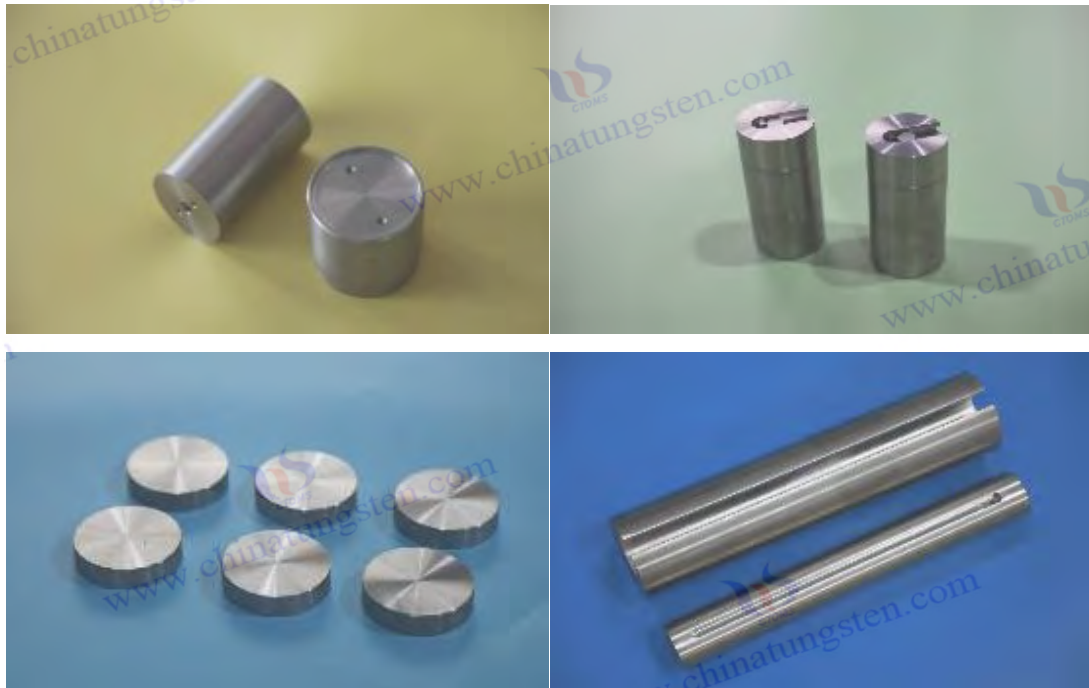
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