

What Are Tungsten Alloy Sheets

中钨智造科技有限公司

CTIA GROUP LTD

CTIA GROUP LTD

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

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INTRODUCTION TO CTIA GROUP

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

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

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

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



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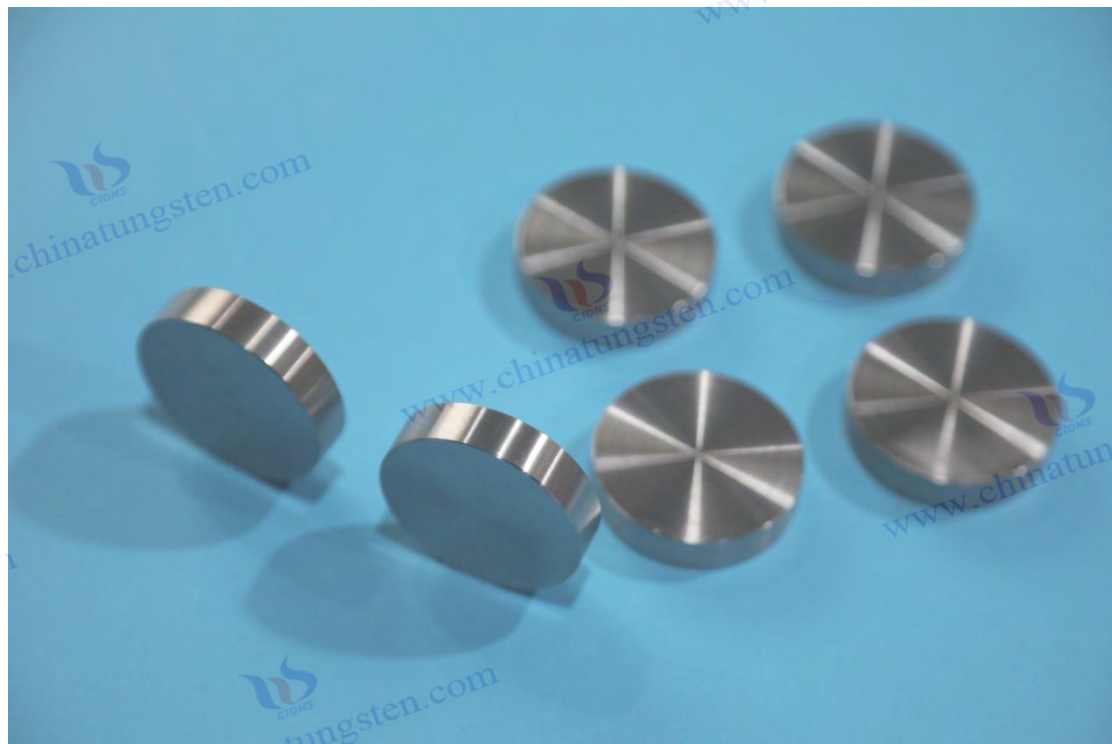
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CTIA GROUP LTD Tungsten Alloy Sheets

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Chapter 1: Basic Understanding of Tungsten Alloy Sheets

1.1 The concept of tungsten alloy sheets

Tungsten alloy sheets are materials with tungsten as the main component, which are alloyed and processed into thin sheets. This material plays an important role in industrial applications because it combines the high density and high melting point of tungsten with improved processing performance and mechanical behavior through the addition of other elements. The advent of tungsten alloy sheets has enabled tungsten, a metal that was previously difficult to process, to be used in sheet form in various engineering applications.

tungsten alloy sheets typically revolves around a high tungsten content, with other elements chosen to optimize overall performance. Common alloy systems include combinations of tungsten with nickel, iron, or copper, which form a binder phase during sintering, helping the tungsten particles to bond better. The sheet thickness is often controlled to within a few millimeters, or even down to the micrometer level, depending on the specific manufacturing process and application requirements. The production process begins with powder mixing, followed by pressing, sintering, hot working, and cold working, ultimately yielding sheets with smooth surfaces and regular edges.

In terms of performance, tungsten alloy sheets exhibit good density distribution, making them excellent for applications requiring concentrated weight. They also possess a degree of ductility, facilitating subsequent bending, stamping, or cutting operations. The heat treatment process is crucial; by controlling the temperature and cooling rate, the grain size and phase distribution of the material can be adjusted, thereby influencing the balance between hardness and toughness.

Tungsten alloy sheets emphasizes the comprehensive application of materials engineering. It's not simply about rolling tungsten thinner; rather, it involves alloying to transform brittleness into machinability. This material is gaining acceptance in electronics, medical devices, and precision instruments because it meets requirements for dimensional stability and environmental adaptability. With advancements in manufacturing technologies such as laser cutting and precision rolling, the range of tungsten alloy sheet specifications continues to expand, satisfying diverse design needs.

1.1.1 Definition of Tungsten Alloy Sheets

Tungsten alloy sheets are defined as thin, sheet-like alloy materials made from tungsten as a matrix, with the addition of small amounts of other metallic elements such as nickel, iron, or copper, prepared by powder metallurgy and rolled into shape. Tungsten typically dominates in the composition, giving the material its fundamental properties of high density and high hardness, while the addition of alloying elements significantly improves the material's plasticity and processing adaptability.

By definition, the key difference between tungsten alloy sheets and other tungsten products lies in their sheet-like shape and alloy composition. During the manufacturing process, tungsten powder is uniformly

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mixed with other metal powders and then sintered in a liquid phase at high temperature to form a dense microstructure. Subsequently, it is gradually thinned to the desired thickness through multiple rolling passes, accompanied by annealing to release internal stress. This definition reflects the complete transformation chain of the material from powder to finished product.

In practical definitions, the classification of alloy series must also be considered. For example, the tungsten-nickel-iron series emphasizes the balance of mechanical properties, while the tungsten-nickel-copper series focuses more on electrical conductivity. The definitions of these series all revolve around the high melting point of tungsten, ensuring that the material maintains shape stability at high temperatures.

Tungsten alloy sheets also extends to their functional positioning; they are high-performance engineering materials suitable for applications requiring a combination of high density and good formability. This definition is not static; with the exploration of new alloying elements, such as the addition of molybdenum or rhenium, the definition is constantly being enriched to adapt to emerging applications.

1.1.2 Definition and Distinction with Related Materials

Tungsten alloy sheets from other materials requires analysis from multiple dimensions, including composition, processing method, performance characteristics, and application positioning, to ensure that confusion is avoided when selecting materials.

The primary consideration is comparison with pure tungsten sheets. Pure tungsten sheets contain almost no alloying elements, and their production relies on the rolling of high-purity tungsten powder. However, due to the room-temperature brittleness of tungsten, the processing must be carried out at high temperatures, making the finished product prone to cracking. Tungsten alloy sheets, on the other hand, introduce a binder phase through alloying, allowing them to be rolled at lower temperatures, resulting in superior surface quality and suitability for a wider range of forming operations.

Tungsten-copper composite sheets also need to be distinguished. This material is mainly a mechanical mixture of tungsten particles and copper phases, with a high copper content, and is prepared using a melt infiltration method rather than alloy sintering. In contrast, tungsten alloy sheets form a solid solution structure, with more uniform miscibility between copper or iron and nickel, resulting in differences in the coefficient of thermal expansion and thermal conductivity.

Molybdenum alloy sheets are another common comparison. Molybdenum has a lower density and melting point than tungsten, and its sheets perform well in vacuum environments, but its high-temperature strength is not as good as tungsten alloy sheets. Molybdenum sheets are more suitable for electronic vacuum devices, while tungsten alloy sheets are more advantageous in applications requiring higher mass inertia.

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Compared to cemented carbide sheets, tungsten alloy sheets do not contain carbide phases. Cemented carbide sheets are mainly composed of tungsten carbide particles and cobalt binders, exhibiting extremely high hardness but limited toughness, and are primarily used in cutting tools. Tungsten alloy sheets, on the other hand, prioritize a balance between density and ductility, making them suitable for balancing components or shielding parts.

These definitions clearly define the position of tungsten alloy sheets: they are sheets that balance density, processability, and stability, filling specific performance gaps in civilian industries. This distinction helps engineers match materials to specific needs.

1.2 The Development and Research Significance of Tungsten Alloy Sheets

Tungsten alloy sheets have undergone a complete evolution from pursuing single performance characteristics to optimizing comprehensive performance. Its development is driven by both the characteristics of tungsten resources and advancements in processing technology, as well as the continuous industrial demand for high-density, high-stability materials. Early tungsten materials mainly appeared in simple forms such as filaments and sputtering targets. With the improvement of powder metallurgy processes and the increasing demands for the machinability of high-density materials, tungsten alloy sheets gradually became an independent research and production direction. In the mid-to-late 20th century, the maturity of liquid-phase sintering technology provided a reliable means of densifying tungsten alloys, and the subsequent introduction of multi-pass rolling and controlled annealing processes truly realized the transformation from bulk to thin sheet morphology. This process not only expanded the application boundaries of tungsten but also laid the foundation for subsequent functionalization and lightweight design. Currently, research on tungsten alloy sheets has expanded from traditional tungsten-nickel-iron and tungsten-nickel-copper systems to multiple cutting-edge directions such as rare earth doping, nanocrystalline strengthening, and gradient structure design, reflecting a trend of deep integration between materials science and engineering needs.

1.2.1 Development Context Based on Tungsten Resource Utilization

As a strategic metal with relatively limited reserves but wide distribution, the efficient utilization of tungsten has always been an important aspect of materials development. Early tungsten resources were mainly used for cemented carbide production, while the remaining low-grade ore or recycled materials were difficult to process further. The emergence of tungsten alloy sheets has provided a new conversion path for medium- and low-grade tungsten resources, allowing previously potentially wasteful tungsten powder to enter high-value-added fields.

Around the 1950s, researchers discovered that adding ferronickel or copper nickel could significantly lower the brittle transition temperature of tungsten. This discovery directly led to the development of the first generation of tungsten heavy alloys, primarily used in bulk form for civilian balancing components. Subsequently, with advancements in rolling equipment precision and annealing processes, the thickness gradually decreased from the initial centimeter level to the millimeter level, and then to tens of

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micrometers today, achieving a shift in resource utilization from extensive to intensive. In the 21st century, the industrial application of advanced sintering technologies such as hot isostatic pressing and spark plasma sintering has further improved billet density and microstructure uniformity, reduced subsequent rolling passes, and lowered energy consumption and tungsten loss rates.

In recent years, the production of tungsten alloy sheets has begun to focus on resource recycling throughout the entire process. For example, scrap materials, rolled oxide scale, and discarded parts from tungsten alloy processing can be converted back into high-purity tungsten powder through hydrogen reduction or zinc melting, and then reintroduced into the batching process, forming a relatively complete closed-loop utilization system. Simultaneously, in response to the declining grade of tungsten resources, some research institutions are attempting to reduce the tungsten content or partially replace it with molybdenum or tantalum while maintaining performance, thus creating a resource-saving alloy system. It can be said that the development trajectory of tungsten alloy sheets is a microcosm of the evolution of tungsten resources from a "high-purity, high-consumption" to a "high-efficiency, circular" utilization model. This process reflects both technological progress and the requirements of sustainable development.

Tungsten Alloy Sheets from a Chemical Engineering Perspective

From a chemical engineering perspective, the research and development of tungsten alloy sheets embodies the engineering solutions to core problems such as multiphase reactions, phase interface control, and heat and mass transfer optimization. Liquid-phase sintering in powder metallurgy is a typical unit operation in chemical engineering, involving tungsten particle rearrangement, wetting and spreading of the binder phase, dissolution-re-precipitation mechanisms, and gas exhaust kinetics. Researchers have achieved precise control over porosity, binder phase distribution, and tungsten particle spheroidization by adjusting parameters such as sintering temperature profiles, hydrogen dew point, and billet loading methods. This is essentially an interdisciplinary application of chemical reaction engineering and materials science.

The rolling and annealing stages involve the coupling of stress and diffusion fields. Finite element simulation and computational fluid dynamics methods, commonly used in chemical engineering, have been widely applied to analyze temperature and stress distribution during rolling and element diffusion behavior during annealing. This helps optimize pass reduction and intermediate annealing regimes, reducing defects such as edge delamination and cracking. Furthermore, surface treatments such as electroless plating and vacuum heat treatment are also typical chemical engineering unit operations that directly affect the oxidation resistance and bonding strength of the sheet material.

Furthermore, research on the behavior of tungsten alloy sheets in corrosive media provides important reference data for material selection in chemical equipment. Through electrochemical testing and immersion experiments, researchers have established corrosion rate models for different alloy systems in acid, alkali, and salt environments, providing theoretical support for extending service life and reducing maintenance costs. From a chemical engineering perspective, tungsten alloy sheets are not only

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The final product but also the result of a highly integrated series of precise and controllable chemical and physical processes. Their research value lies in providing replicable experience for the engineering scale-up of similar high-melting-point, multiphase materials.

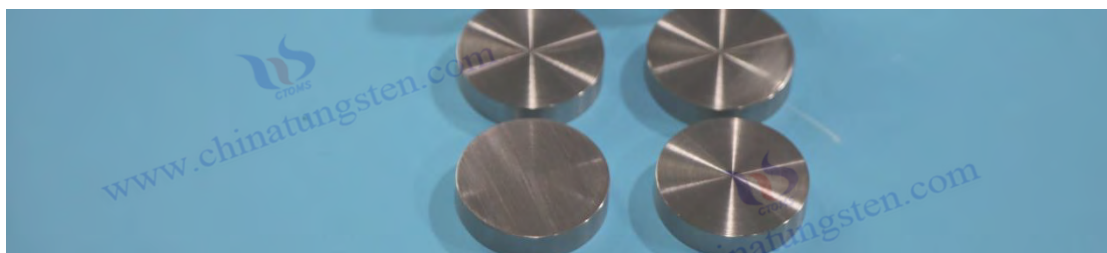
1.2.3 The Status of Tungsten Alloy Sheets in Application Fields

Tungsten alloy sheets have established an irreplaceable position in the modern industrial system, primarily due to the demand for a balance between high density and good machinability. In the field of medical devices, tungsten alloy sheets, with their excellent radiation attenuation capabilities and biocompatibility, have become the preferred material for core components such as collimators and multi-leaf gratings in high-end radiotherapy equipment. Their thickness precision and surface quality affect the accuracy of treatment positioning.

In precision instruments and the electronics industry, tungsten alloy sheets are used as vibration control components and electromagnetic shielding parts, leveraging the inertial advantages of their high density and moderate conductivity. In analytical instruments, high-precision balances, inertial navigation systems, and other equipment, tungsten alloy sheets help achieve a balance between miniaturization and high stability.

Furthermore, tungsten alloy sheets are gradually occupying an important position in vacuum coating and thermal management . As a backplate or heat sink material for sputtering targets, it balances the requirements of high thermal conductivity and low thermal expansion. In recent years, with the rapid development of new energy and next-generation information technology, the demand for high-performance thermal interface materials and shielding materials has continued to grow. Tungsten alloy sheets, with their unique combination of properties, are extending from traditional applications to emerging fields.

It is worth noting that tungsten alloy sheets are not used in isolation, but rather complement other high-performance materials. In some cases, they are used in conjunction with titanium alloys and carbon fiber composites to achieve a balance between lightweighting and functionality. It is this ability to independently perform key functions while also working collaboratively with other materials that has solidified the stable position of tungsten alloy sheets in the modern industrial materials spectrum. With further improvements in processing precision and surface treatment technologies, their application areas still have considerable room for expansion.



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Chapter Two: Classification System of Tungsten Alloy Sheets

2.1 Tungsten Alloy Sheets by Material Composition

Classifying [tungsten alloy sheets](#) by material composition is the most common and intuitive method. This classification reflects the differences in the chemical composition of the binder phase, thus determining the systematic differences in mechanical properties, thermophysical properties, electromagnetic properties, and processing adaptability. Currently, almost all industrially produced tungsten alloy sheets use nickel as the main binder element because nickel has good wettability to tungsten, moderate activation sintering ability, and small thermal expansion mismatch with tungsten. Based on the different second components, two main series have been formed: nickel-iron and nickel-copper. In addition, there are small amounts of nickel-molybdenum, nickel-rhenium, or other experimental systems, but these have not yet reached large-scale sheet production. The tungsten content of the two mainstream systems is usually between 90% and 97%, and the total amount of binder phase is controlled between 3% and 10%. By fine-tuning the ratio and thermomechanical processing parameters, the final properties can be controlled within a wide range.

2.1.1 Nickel-iron tungsten alloy sheet

Nickel-iron tungsten alloy sheets were the first type of tungsten alloy sheets to be industrialized and still dominate the market today. Their typical composition ranges from 90% to 97% W, 2.5% to 7% Ni, and 0.5% to 3% Fe, with the Ni/Fe mass ratio usually maintained between 7:3 and 8:2. This ratio design stems from extensive experimental screening in the mid-20th century, which showed that this range can form an appropriate amount of liquid phase during the liquid-phase sintering stage, promoting sufficient rearrangement of tungsten particles while avoiding excessive agglomeration of the binder phase or the appearance of brittle phases.

The nickel-iron system is that the binder phase is an iron-nickel solid solution, exhibiting significant ferromagnetism, thus resulting in a strong overall magnetic response in the material. This characteristic gives it a natural advantage in applications requiring magnetic shielding or magneto-actuation. Simultaneously, the addition of iron significantly reduces the stacking fault energy of the binder phase, promoting the dissolution-precipitation process in the later stages of sintering, making tungsten particles more spherical, and resulting in higher interfacial bonding strength between the tungsten and binder phases. Macroscopically, this manifests as higher tensile strength and fracture toughness.

In sheet processing, nickel-iron systems exhibit good thermoplasticity and cold working properties. After high-temperature sintering, the billet can be hot-rolled multiple times at 1100°C–1300°C, followed by intermediate annealing and cold rolling to ultimately thin to below 0.05mm. Edge cracks are less likely to occur during rolling, resulting in a high yield. The heat treatment regime significantly affects the final properties: low-temperature, long-time annealing retains fine tungsten particles and fibrous structure, achieving higher strength; high-temperature, short-time annealing promotes tungsten particle coarsening and homogenization of the binder phase, improving ductility.

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In terms of surface treatment, nickel-iron tungsten alloy sheets are easily electroless plated with nickel, gold, or silver, and can also undergo diffusion aluminum plating in a vacuum environment to form a protective layer, further improving their oxidation and corrosion resistance. Currently, this series of sheets is widely used in civilian precision components requiring both high density and a certain level of mechanical reliability, such as weights for high-end analytical balances, balance blocks for inertial instruments, and vibration damping sheets for optical instruments. With advancements in rolling equipment and heat treatment technology, the thickness uniformity and flatness of nickel-iron tungsten alloy sheets have reached the micrometer level, meeting the stringent requirements of high-end instruments for minute quality deviations.

2.1.2 Nickel-copper tungsten alloy sheet

Nickel-copper tungsten alloy sheets are non-magnetic tungsten alloy sheets developed from nickel-iron alloys. Their typical composition is 90%–96% W, 3%–8% Ni, and 1%–5% Cu, with a Ni/Cu mass ratio typically between 3:1 and 7:3. The introduction of copper completely eliminates the macroscopic ferromagnetism of the material, making it the only choice for environments with strong magnetic fields or high electromagnetic compatibility requirements. Simultaneously, copper's high thermal and electrical conductivity endows this series of sheets with superior thermal diffusion and electrical contact performance.

From a microscopic perspective, the binder phase in the nickel-copper system is also a face-centered cubic solid solution. However, due to the infinite miscibility of copper and nickel, the binder phase exhibits better compositional uniformity. The liquid phase emergence temperature during sintering is slightly lower than in the nickel-iron system, which is beneficial for lowering the sintering temperature and reducing abnormal tungsten particle growth. The spheroidization degree of tungsten particles is generally higher than in the nickel-iron system, resulting in higher interface cleanliness. This often leads to slightly higher elongation for the same tungsten content, but a slight decrease in tensile strength, reflecting a trade-off between strength and plasticity.

In terms of processing characteristics, nickel-copper alloys are more sensitive to oxidation. High-temperature rolling must be carried out under a protective atmosphere or vacuum; otherwise, a loose oxide layer easily forms on the surface, affecting subsequent cold rolling. The cold work hardening rate is slightly lower than that of nickel-iron alloys, making them suitable for high-reduction rolling and beneficial for producing ultra-thin foils (thicknesses up to 20 μm). The annealing process window is wide, and the material is not sensitive to overheating, which facilitates continuous production lines.

In terms of surface treatment, nickel-copper alloys inherently possess good corrosion resistance and electrical contact properties, often requiring only direct polishing or light chemical cleaning to meet requirements, eliminating the need for complex plating processes. In terms of applications, this series of sheets is mainly used in collimator blades for medical radiotherapy equipment, electromagnetic shielding covers, vacuum sputtering target backplates, heat sinks, and other applications requiring non-magnetic, high thermal conductivity, or high electrical conductivity. In recent years, with the increasing demand

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for heat dissipation in 5G communications and high-power electronic devices, the thinning and composite applications of nickel-copper tungsten alloy sheets are rapidly expanding, demonstrating strong vitality.

2.1.3 Tungsten-copper alloy sheet

Tungsten-copper alloy sheets occupy a special position in the classification system. Strictly speaking, they belong to pseudo-alloys or metal matrix composites, rather than solid solution tungsten alloys in the traditional sense. The typical composition range is 50%–90% W and 10%–50% Cu, with the two phases being almost immiscible. Copper is distributed in a continuous or semi-continuous network within the tungsten framework. Due to the absence of an alloying binder phase, tungsten-copper sheets differ fundamentally from the aforementioned nickel-based tungsten alloy sheets in microstructure, performance characteristics, and processing methods.

tungsten- copper sheets mainly employs either the melt infiltration method or the direct activation sintering method. The melt infiltration method first presses and sintersects a porous tungsten framework, then allows molten copper to infiltrate into the pores at a temperature slightly above the melting point of copper. Activation sintering, on the other hand, involves premixing a small amount of nickel or cobalt into tungsten powder and directly densifying it in a single step at 1300°C–1400°C. Both processes produce sheets with extremely high thermal and electrical conductivity, typically ranging from 180 to 220 W/(m·K), and electrical conductivity reaching 40%–55% IACS, with a coefficient of thermal expansion that matches well with semiconductor materials.

In sheet processing, tungsten copper exhibits excellent hot and cold working properties due to the presence of the copper phase. Grades with a tungsten content of 70%–80% can be directly rolled at room temperature with large reductions, easily achieving a finished thickness of less than 0.1 mm with a high surface finish and almost no need for intermediate annealing. When the tungsten content exceeds 85%, warm rolling and a protective atmosphere are required. The most prominent advantages of tungsten copper sheets are their non-magnetic nature, excellent thermal conductivity, and strong resistance to arc erosion. Therefore, they have gained widespread recognition in civilian and industrial fields where high-voltage electrical contacts, vacuum switch electrodes, resistance welding electrodes, electronic packaging heat sinks, and rocket engine nozzle throat liners require simultaneous resistance to high temperatures, arcs, and thermal shock. In recent years, with the explosive growth in demand for heat dissipation in high-power IGBT modules and third-generation semiconductor substrates, ultra-thin high-tungsten-content tungsten copper sheets (thickness <0.3 mm, tungsten content ≥85%) have become a research and production hotspot.

2.1.4 Tungsten-silver alloy sheet

Tungsten-silver alloy sheets also belong to a pseudo-alloy system, with silver as a soft, highly conductive phase and tungsten as a hard framework; the two are mutually insoluble. Their composition typically consists of 50%–80% W and 20%–50% Ag. The preparation process is highly similar to that of tungsten-

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copper alloys , primarily using high-temperature melting and infiltration, but powder mixing followed by high-pressure solidification can also be employed. Because silver has a lower melting point (961°C) than copper, the melting and infiltration temperature is correspondingly lower, resulting in a wider process window and milder equipment requirements.

Tungsten-silver sheets surpass tungsten-copper sheets in both electrical and thermal conductivity. Electrical conductivity easily reaches 60%–80% IACS, and thermal conductivity ranges from 250 to 380 W/(m·K), while maintaining the high hardness and ablation resistance of tungsten. More importantly, the silver oxide formed under an electric arc has a high vapor pressure, easily carrying away thermal damage, giving the material excellent resistance to arc erosion and welding. In terms of processing performance, tungsten-silver sheets with a silver content of 30% or higher can be rolled to below 0.05 mm in a nearly completely cold state , with minimal edge cracking and a silvery-white surface exhibiting excellent visual appeal.

Currently, tungsten silver sheets are mainly used in low- and medium-voltage electrical contacts, precision relay contacts, sliding electrical contacts, and as substrates for coating the inner walls of certain special waveguides. In fields such as high-end circuit breakers for civilian use, automotive relays, and aviation relays, tungsten silver sheets have gradually replaced traditional silver-cadmium and silver-nickel materials due to their long lifespan, low contact resistance, and low material transfer characteristics .

2.1.5 Other binder phase tungsten alloy sheets

In addition to the aforementioned mainstream systems, some tungsten alloy sheets using novel or composite binder phases have emerged in recent years. These are mainly in the transition stage from laboratory to industrialization, or are being produced in small batches to meet specific functional requirements.

Tungsten-nickel-cobalt system: Adding 1% to 3% cobalt to nickel-iron or nickel-copper base can significantly improve the strength of the binder phase and the ability to resist softening at high temperatures, making it suitable for heat sinks or structural components that require higher operating temperatures.

Tungsten-nickel-molybdenum system: By partially replacing tungsten with molybdenum (5% to 20%), the overall coefficient of thermal expansion is reduced while maintaining high density, improving thermal matching with ceramics or glass. It is often used in electronic packaging shells or vacuum sealing transition sheets.

Tungsten-rare earth system: Adding trace amounts of rare earth oxides such as La_2O_3 , Y_2O_3 , and CeO_2 improves recrystallization temperature and high - temperature strength through dispersion strengthening mechanism, while refining tungsten grains and improving crack resistance during thin sheet rolling .

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TiC , ZrC and other carbide particles are added to the nickel-based binder phase to form a third phase reinforcement, which significantly improves hardness and wear resistance. It is mainly used for wear-resistant linings or precision mold inserts.

Tungsten-high-entropy binder system: a new research direction, using high-entropy alloy powders such as FeCoNiCrMn and FeCoNiCrAl as binder phases to achieve higher strength and oxidation resistance while maintaining high density. Currently, it is only in the laboratory foil stage.

2.2 Tungsten Alloy Sheets by Core Performance

Classifying tungsten alloy sheets according to their core properties reflects the direct demand for the material's dominant function in engineering applications. Currently, tungsten alloy sheets can be broadly classified into three categories based on their core properties: high-density, high-hardness, and corrosion-resistant/wear-resistant. While there is some overlap among these three categories, their dominant functions differ.

2.2.1 High-density tungsten alloy sheet

High-density tungsten alloy sheets are the most produced and widely used type of tungsten alloy sheet. Their core design goal is to maximize theoretical density while retaining sufficient machinability and mechanical reliability. Typical densities range from 17.0 to 18.8 g/cm³, with some reaching nearly 19.0 g/cm³, far exceeding most engineering metals.

These sheets are almost entirely composed of nickel-iron or nickel-copper alloys with a tungsten content of 93%–97%, and the total binder phase is controlled at 3%–7%. To further approximate the theoretical density, high-purity fine tungsten powder, extended liquid-phase sintering holding time, and secondary pressing after hot isostatic pressing are commonly used in production to reduce porosity to below 0.1%. The rolling process mainly involves large-reduction hot rolling followed by multi-pass cold rolling, coupled with strict intermediate vacuum annealing to ensure that the density uniformity deviation in the thickness direction does not exceed 0.5%.

High-density tungsten alloy sheets exhibit significant advantages in applications requiring concentrated mass and reduced volume. In the medical field, multi-leaf collimators in radiotherapy equipment commonly utilize 0.15–0.5 mm thick 93W-4.9Ni-2.1Fe sheets. Their high density leads to improved radiation shielding efficiency and volume savings, directly enhancing treatment accuracy and bed turnover. In the field of precision instruments, this material is also widely used for counterweights and balance plates in analytical balances, gyroscopes, and inertial navigation systems. The thickness is typically between 0.05 and 2 mm, with a density tolerance within ± 0.05 g/cm³.

In recent years, with the increasing demand for local counterweights in electric vehicles and wearable devices, high-density tungsten alloy sheets have begun to develop towards ultra-thin (<0.1 mm) and high

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surface finish ($Ra \leq 0.1 \mu m$). Some high-end products have achieved composite lamination with polymers or aluminum alloys, further expanding their application space in the consumer electronics field.

2.2.2 High-hardness tungsten alloy sheet

High-hardness tungsten alloy sheets prioritize significantly improving surface and overall hardness, typically requiring a Vickers hardness between 380 and 550 HV30, with some reinforced grades exceeding 600 HV30. This type of sheet achieves hardness enhancement through three methods: composition optimization, deformation strengthening, and second-phase dispersion.

Common technical approaches include: increasing the tungsten content to 95%–98% to reduce the proportion of soft binder phase; using a high cobalt-nickel-iron binder phase (Co content 3%–8%) to utilize the solid solution strengthening and precipitation strengthening effects of cobalt; cold rolling with a total processing rate exceeding 70% to form a strong fibrous texture and high-density dislocations; introducing carbide particles such as TiC, ZrC, and WC (volume fraction 2%–8%) for dispersion strengthening; and low-temperature long-term aging to precipitate fine intermetallic compounds from the binder phase.

High-hardness tungsten alloy sheets significantly improve scratch resistance, indentation resistance, and fatigue resistance while maintaining a certain level of ductility. In the field of precision molds, when used as stainless steel mold inserts for stamping mobile phone frames, tungsten alloy sheets with a hardness of 450 HV or higher can extend mold life by 3 to 5 times compared to traditional high-speed steel. In optical glass hot-pressing molds, tungsten alloy sheets with a surface hardness of 520 HV, combined with ion-implanted nitrided tungsten alloy sheets, can effectively resist high-temperature glass adhesion and abrasive wear.

Furthermore, in high-end watchmaking, high-hardness tungsten alloy sheets are processed into rotors or micro-gears, utilizing their high density to increase inertia while relying on their high hardness to ensure wear resistance during long-term operation. In recent years, some manufacturers have used a composite process of vacuum heat treatment and deep cryogenic treatment to create a gradient of surface hardness on tungsten alloy sheets, further balancing surface wear resistance with core toughness.

2.2.3 Corrosion-resistant and wear-resistant tungsten alloy sheets

Corrosion-resistant and wear-resistant tungsten alloy sheets are mainly developed for working conditions such as chemical, marine, and food processing where they come into contact with corrosive media or abrasive environments. Their core purpose is to improve the service life of materials under acid, alkali, salt, and abrasive erosion conditions.

The main implementation path includes: selecting a high-nickel copper or nickel-chromium binder phase system, increasing the nickel content to 8%–12% and the chromium content to 2%–5% to form self-passivation capability; chemically plating nickel-phosphorus or nickel-boron on the surface, or vacuum

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plating hard coatings such as CrN, TiAlN, and DLC with a thickness of 10–50 μm ; adding trace amounts of rare earth elements or boron and phosphorus to promote the formation of a denser protective oxide film in the binder phase; and using a high-energy ball milling + spark plasma sintering process to obtain nanocrystalline or amorphous-nanocrystalline composite structures.

In applications such as impeller guards for chemical pumps, inserts for food-grade agitators, and valve plates for seawater desalination equipment, tungsten alloy sheets with a high-nickel surface coating and substrate exhibit excellent resistance to pitting and crevice corrosion. In highly abrasive environments such as lining slurry pipelines and grading screens in mineral processing equipment, the weight loss of TiC- dispersion-strengthened tungsten alloy sheets is only 1/5 to 1/8 that of high- chromium cast iron.

It is worth mentioning that some corrosion- and wear-resistant tungsten alloy sheets also adopt a gradient structure design: the surface layer is enriched with high-chromium-nickel binder phases and hard phases, while the core maintains the traditional nickel-iron ratio, ensuring both corrosion and wear resistance without sacrificing overall toughness and machinability. This structural design represents the latest strategy for tungsten alloy sheets in complex service environments.

2.3 Classification of Tungsten Alloy Sheets by Size and Specifications

Classifying tungsten alloy sheets by size is the most direct communication language between manufacturers and downstream users. Thickness is the most critical parameter determining processing difficulty, cost, and application direction. While width and length also have an impact, they can usually be flexibly adjusted through shearing, laser cutting, or waterjet cutting once the thickness is determined. Currently, the industry has established relatively unified thickness range classifications, which reflect both the boundaries of processing capabilities and correspond to different typical application scenarios.

2.3.1 Ultra-thin tungsten alloy sheet (thickness < 0.1 mm)

Ultra-thin tungsten alloy sheets typically refer to foils with a finished thickness between 0.005 mm and 0.099 mm, with the thinnest reaching below 0.008 mm. The preparation of these sheets represents the highest level of tungsten alloy rolling technology, requiring extremely high standards for raw material purity, billet uniformity, roll precision, and a clean environment.

The production of ultrathin foil typically uses nickel-iron or nickel-copper systems with a tungsten content of 90%–95%, with a slightly higher proportion of binder phase to ensure cold working performance. The billet must first be pre-formed into a 2–5 mm thick plate through hot isostatic pressing or vacuum hot rolling, followed by multiple cold rolling passes. The reduction in each pass is strictly controlled at 5%–15%, and the total processing yield often exceeds 95%. Intermediate annealing must be carried out under high vacuum or high-purity hydrogen atmosphere to avoid brittle fracture caused by any oxidation inclusions. The surface finish of the finished foil can reach Ra below 0.05 μm , and the thickness tolerance is controlled within ± 0.003 mm.

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Ultrathin tungsten alloy sheets are mainly used in the thinnest blades of multi-leaf collimators in medical radiotherapy equipment, flexible radiation shielding curtains, vibration damping films for precision instruments, automatic rotors in high-end watches, and some flexible electronic substrates. In recent years, with the demand for ultrathin, high-density materials in wearable medical devices and foldable screen phones, nickel-copper based ultrathin foils with a thickness of 0.03–0.07 mm have begun to be combined with polymers to form new functional films that combine shielding and flexibility.

2.3.2 Tungsten alloy sheets of conventional thickness (0.1–10 mm)

The thickness range of 0.1 mm to 10 mm is currently the largest and most widely used range, accounting for more than 90% of the total production of tungsten alloy sheets. The processing technology for this thickness range is highly mature, the cost is relatively controllable, and the dimensional accuracy and performance consistency can meet the requirements of most industries.

This thickness range covers the entire process chain from hot rolling to cold rolling finishing. After multiple hot rolling passes at 1100–1300°C, the thickness of the billet is reduced to 3–8 mm, and then it is transferred to cold rolling and multiple intermediate annealing processes to finally obtain the required specifications. The thickness tolerance is generally controlled within ± 0.01 – ± 0.05 mm, and the surface can be polished, sanded, or chemically etched as needed.

Standard thickness tungsten alloy sheets cover almost all mainstream applications: 0.1–0.5 mm for collimator blades and shielding plates; 0.5–2 mm for counterweights, vibration dampers, and heat sinks; 2–6 mm for mold inserts and target backplates; and 6–10 mm are mostly used as structural supports or precast blanks. This diversity in thickness is also reflected in surface treatments, allowing for nickel, gold, silver, DLC plating, or direct anodizing to form colored decorative layers, meeting various needs from industrial functions to consumer product aesthetics.

2.3.3 Thick-walled tungsten alloy sheet (thickness > 10 mm)

Tungsten alloy sheets with a thickness exceeding 10 mm are generally referred to as thick plates or thick-walled sheets, with the maximum thickness reaching over 50 mm. Although these products account for a small percentage of the total tungsten alloy sheet production, their high value per sheet and difficulty in processing make them a key production capacity that many manufacturers retain.

Thick-walled sheets are primarily produced through hot rolling, supplemented by cold rolling. Sintered billets typically have diameters of 300–500 mm. Hot rolling temperatures are controlled at 1350–1450°C, with a reduction of 20%–30% per pass until the thickness reaches 12–15 mm, at which point they are transferred to warm rolling or cold rolling for finishing. To prevent edge cracks, cladding rolling or lateral restraint rolling techniques are commonly employed. The finished product thickness tolerance is generally ± 0.1 – ± 0.3 mm, and the surface requires milling or grinding to remove the decarburized layer and oxide scale.

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Thick-walled tungsten alloy sheets are mainly used in collimator bases for large medical linear accelerators, shielding bodies for industrial CT detectors, balance discs for large inertial instruments, counterweights for oil drilling, and heat absorbers in high-energy physics experiments. Due to their large size and heavy weight, their transportation and machining often require specialized tooling. Therefore, downstream users often adopt near-net-shape designs to minimize subsequent cutting.

2.3.4 Custom-sized tungsten alloy sheets

Custom-sized tungsten alloy sheets refer to various irregular shapes, extra-wide, extra-long, or composite structural sheets that exceed standard rectangles and thicknesses. These products are manufactured entirely according to customer drawings, reflecting the trend of tungsten alloy sheet production shifting from "standardized supply" to "solution provision."

Common special types include: preformed sheets with deep-drawn steps, perforated sheets with through holes or countersunk holes, ultra-wide sheets with a width exceeding 600 mm, ultra-long strips with a length exceeding 2 m, functional sheets with microstructure arrays on the surface, and laminated sheets directly composited with copper, aluminum, molybdenum, ceramics, etc. Production often requires special processes such as specialized molds, laser cutting, CNC milling, vacuum brazing, or hot isostatic pressing (HIP) encapsulation.

For example, some high-end medical devices require tungsten alloy sheets with dovetail grooves 500 mm wide, 0.2 mm thick, and with an edge precision of 0.05 mm; some aerospace optical instruments require tungsten alloy vibration damping sheets with mirror-polished surfaces and complex curved bends. Although these specialized products have high unit prices, the overall cost is actually lower because they directly reduce the secondary processing steps for customers.

2.4 Tungsten Alloy Sheets by Application Scenarios

Classifying tungsten alloy sheets by their application scenarios provides a clearer picture of the material's actual value across different industries. Currently, the main application areas of tungsten alloy sheets have formed a relatively stable pattern, covering medical, industrial manufacturing, electronic information, and other specialized scenarios.

2.4.1 Tungsten alloy sheets for national defense and military use

Tungsten alloy sheets are primarily used in the defense and military industries due to their high density, high strength, and good toughness. These applications involve components requiring concentrated mass, structural stability, or specific functionalities. The high tungsten content of tungsten alloy sheets provides inertial advantages, while the binder phase optimizes machinability, supporting precision forming and surface treatment.

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In balancing counterweights, tungsten alloy sheets adjust the mass distribution to help the system operate stably, and their uniform thickness ensures accuracy. In protective structural applications, tungsten alloy sheets utilize their radiation attenuation capabilities to provide thin-layer, highly efficient shielding, while composite designs enhance overall strength. The thermal stability of tungsten alloy sheets supports high-temperature environments, and the surface coating improves corrosion resistance.

Applications prioritize reliability, with tungsten-nickel-iron systems being common, ensuring chemical stability for long-term service. The role of tungsten alloy sheets in defense and military industries has facilitated component miniaturization, and high density reduces bulk footprint.

2.4.2 Tungsten alloy sheets for industrial manufacturing

In industrial manufacturing, tungsten alloy sheets leverage their combined advantages of high density and excellent wear resistance, making them widely used in various balancing components, vibration damping components, wear-resistant liners, and mold parts. In precision instruments, counterweights, analytical balance weights, and inertial navigation components often utilize nickel-iron based high-density sheets to improve equipment stability through precise control of mass distribution. Vibration control plates in high-speed rotating machinery utilize the high elastic modulus and moderate damping characteristics of tungsten alloy sheets to effectively suppress resonance.

In the mold industry, tungsten alloy sheets are processed into stamping die inserts, hot-pressing glass mold cores, or wire drawing die inlet bushings. Their high hardness and resistance to high-temperature softening significantly extend the service life of the molds. Wear-resistant liners, valve plates, and nozzles in oil and mining equipment also often use carbide-reinforced tungsten alloy sheets to cope with the dual effects of abrasive erosion and corrosive media.

2.4.3 Tungsten alloy sheets for nuclear and medical applications

In the medical and nuclear industries, tungsten alloy sheets are primarily used for radiation shielding and collimation components. Multi-leaf collimators in radiotherapy equipment commonly use nickel-iron or nickel-copper based sheets with a thickness of 0.1–2 mm, achieving flexible shaping of the radiation beam through layering. Compared to traditional lead, tungsten alloy sheets are non-toxic, high-strength, and maintain sharp edges easily, making them the current mainstream choice. Detector collimators in nuclear medicine imaging equipment and PET/CT anti-scatter grids also extensively use tungsten alloy sheets to improve imaging resolution. In industrial non-destructive testing, such as X-ray flaw detection of large castings and gamma-ray inspection of pipe welds, shielding boxes or collimation windows made of tungsten alloy sheets are also required. In the nuclear industry, thicker tungsten alloy plates are occasionally used for the lining of radiation shielding containers and for local reinforcement of waste storage tanks to achieve efficient shielding within limited spaces. With the increasing prevalence of proton and heavy ion therapy equipment, the demand for ultra-thin, highly uniform tungsten alloy sheets continues to grow.

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2.4.4 Tungsten alloy sheets for electronic information applications

The demand for tungsten alloy sheets in the electronics and information industry is mainly concentrated in three areas: thermal management, electromagnetic shielding, and sputtering target materials. High-power chips, 5G base station power amplifiers, lasers, and other devices often use tungsten-copper or nickel-copper based tungsten alloy sheets as heat sinks or extension layers, leveraging their similar coefficient of thermal expansion to semiconductor materials and high thermal conductivity to effectively reduce junction temperature. Tungsten alloy sheets are also frequently used as backplates for vacuum sputtering targets, bonded to pure tungsten or tungsten-rhenium targets through brazing or explosive bonding, ensuring bonding strength while controlling overall cost.

In the field of electromagnetic compatibility (EMC), non-magnetic tungsten alloy sheets are used to fabricate shielding covers, absorbing patches, or grounding springs for devices sensitive to magnetic fields, such as mobile phones, medical electronics, and avionics. Some high-end audio equipment utilizes high-density tungsten alloy sheets to create speaker diaphragm weight rings to improve low-frequency response. In recent years, with the rapid development of third-generation semiconductor (gallium nitride, silicon carbide) devices, the demand for thinner, more thermally conductive tungsten copper sheets has increased rapidly, driving continuous optimization of related processes.

2.4.5 Other Special Tungsten Alloy Sheets

Beyond the main applications mentioned above, tungsten alloy sheets also play unique roles in some specific scenarios. In the high-end watchmaking industry, polished tungsten alloy sheets are used to create automatic rotors, increasing winding efficiency and providing a substantial feel when worn. In the sporting goods sector, some golf club heads are inlaid with tungsten alloy sheets to adjust the center of gravity and improve shot stability. In the jewelry and decorative arts sector, gold-plated or black-plated tungsten alloy sheets are used for watch cases, ring inner bands, or decorative clasps, gaining popularity due to their scratch-resistant surface and unique metallic luster.

In scientific research, tungsten alloy sheets are often processed into high-density target sheets, sample holders, or local linings for vacuum chambers, used in synchrotron radiation sources and particle accelerator experiments. In art restoration and cultural relic preservation, tungsten alloy sheets are also occasionally used for precision weights or structural reinforcement. Furthermore, some emerging interdisciplinary fields, such as wearable device vibration motor weights, drone gimbal balance plates, and racing car wheel weights, are gradually adopting tungsten alloy sheets to achieve a combination of miniaturization and high performance.



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Chapter Three Alloying Principles and Composition Systems of Tungsten Alloy Sheets

3.1 Chemical Principles of Tungsten Alloy Sheet Alloying

Tungsten alloy sheets essentially involves introducing small amounts of other metals or compounds into tungsten to significantly improve its room-temperature plasticity, high-temperature strength, oxidation resistance, and processing performance while maintaining tungsten's inherent high density and high melting point. Tungsten itself has a body-centered cubic structure and a large atomic radius. Pure tungsten has almost no mobile slip systems at room temperature, and its brittle transition temperature is as high as 300–400°C or higher, making it extremely prone to cracking during room-temperature rolling. Through alloying, the introduced face-centered cubic or hexagonal close-packed binder phase provides continuous plastic deformation channels for tungsten particles. Simultaneously, during sintering and hot working, a series of physicochemical processes occur, including dissolution-reprecipitation, interface wetting, and interphase stress regulation, ultimately forming a typical two-phase composite structure in which tungsten particles are encapsulated by the binder phase. This structure retains the hard framework of tungsten while achieving macroscopic plasticity and toughness far exceeding that of pure tungsten, creating conditions for subsequent large deformation rolling into thin sheets.

3.1.1 Phase diagram analysis of tungsten with other metallic elements

Tungsten is infinitely miscible with most transition metals in the liquid state, but its solubility in the solid state is extremely low. This constitutes the basic phase diagram characteristic of tungsten alloy sheet alloying. The W-Ni binary phase diagram shows that the solid solubility of nickel in tungsten does not exceed 2 at% at 1500°C, and is almost zero when cooled to room temperature, while the solubility of tungsten in nickel is slightly higher but still limited. W-Fe, W-Cu, W-Co, W-Mo and other systems also exhibit similar characteristics: a wide liquid phase region exists at high temperatures, which facilitates liquid phase sintering; at low temperatures, almost completely immiscible eutectic or peri-eutectic systems are formed. It is this characteristic of "high-temperature miscibility and low-temperature separation" that allows tungsten alloys to achieve spheroidization and densification of tungsten particles through the Ostwald ripening mechanism during the liquid phase sintering stage, while forming a two-phase structure with clearly separated tungsten particles and binder phase after solid-state cooling.

The W-Cu and W-Ag systems are more extreme; even in the liquid state, they are only partially miscible and do not form compounds at all in the solid state, making them typical pseudo-alloys. W-Mo and W-Re, on the other hand, allow molybdenum and rhenium to form continuous solid solutions with tungsten. This characteristic can be utilized to adjust the coefficient of thermal expansion or increase the recrystallization temperature by partially replacing tungsten with molybdenum or rhenium. The W-Ni-Fe ternary phase diagram is the most commonly used in actual production. Near the liquidus appearance temperature, there is a broad two-phase region of liquid phase + tungsten solid phase. When the nickel-iron ratio is 7:3 to 8:2, the amount of liquid phase is moderate, sufficient to wet the tungsten particles without causing the billet to collapse. Phase diagram analysis provides a direct basis for composition design: the total amount of binder phase is usually controlled at 3% to 10% by volume; too low a volume

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results in insufficient wetting and poor density, while too high a volume significantly reduces density and hardness.

3.1.2 Chemical Mechanisms of Solid Solution Strengthening and Dispersion Strengthening

tungsten alloy sheets comes from the binder phase. Elements such as nickel, iron, copper, and cobalt are infinitely miscible in the face-centered cubic γ - phase, forming substitutional solid solutions. The dissolution of larger atomic radii tungsten, molybdenum, and rhenium into the nickel-based binder phase causes lattice distortion, hindering dislocation movement and thus increasing the yield strength of the binder phase itself. The addition of cobalt is particularly effective because it reduces stacking fault energy, promotes cross-slip and twinning, and further enhances work hardening capacity. Iron and copper, to some extent, reduce the stacking fault energy of the binder phase, making it easier for deformation to coordinate and indirectly improving overall plasticity.

Dispersion strengthening is the key mechanism for tungsten alloy sheets to achieve high strength and high-temperature performance. During sintering, the solubility of tungsten in the binder phase decreases sharply with decreasing temperature, causing supersaturated tungsten atoms to reprecipitate as extremely fine particles during the cooling stage, pinning them at the tungsten/binder phase interface and forming an interface strengthening layer. Simultaneously, artificially added second-phase particles such as TiC, ZrC, HfC, and rare earth oxides do not dissolve during sintering and are uniformly distributed in the binder phase or at the interface, effectively hindering dislocation and grain boundary migration. In recent years, nanocrystalline tungsten alloy sheets have further controlled the tungsten particle size to below 100 nm, significantly improving strength by utilizing the Hall-Petch relationship. The synergy of these two strengthening mechanisms allows tungsten alloy sheets to maintain high strength levels even above 900°C.

3.1.3 Formation conditions and stability of alloy phases

The main alloying phases in tungsten alloy sheets include tungsten solid solution phase, γ -(Ni,Fe,Cu) binder phase, and possible intermetallic compound or oxide dispersion phases. The formation of the γ -phase depends on the sufficient diffusion and homogenization of binder elements during liquid-phase sintering. The sintering temperature needs to be approximately 50–100°C above the lowest eutectic point and held at that temperature to allow tungsten particles to rearrange and spheroidize. Controlling trace amounts of water vapor in a hydrogen atmosphere affects the oxygen content; too high a content leads to the formation of volatile WO_2 (OH)₂, resulting in tungsten loss, while too low a content results in poor venting and closed pores.

The long-term stability of the binder phase is mainly controlled by the interfacial energy and thermal expansion difference between the tungsten and binder phases. The wetting angle at the interface between tungsten and nickel, iron, and copper is close to 0° at the liquid-phase sintering temperature. After cooling, the interfacial bonding is mainly metallic, resulting in high strength. The residual interfacial stress caused by the difference in thermal expansion coefficients can be partially released during

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annealing, but excessively high temperatures can induce Kirkendall voids or brittle interfacial phases (such as Ni_4W , Fe_7W_6). The addition of trace amounts of rare earth elements or boron and phosphorus can segregate at the interface, forming thin amorphous or compound films, further improving the high-temperature stability of the interface. Under vacuum or neutral atmosphere, tungsten alloy sheets can be used for extended periods above 1000°C without significant phase transformation or microstructure coarsening, while in air, a surface coating is required to protect the binder phase and inhibit preferential oxidation.

3.2 The role and proportion of constituent elements in tungsten alloy sheets

The role and proportion of constituent elements in tungsten alloy sheets are core aspects of alloy design. By rationally selecting and controlling the ratios of tungsten, binder elements, and trace additives, it is possible to optimize the material's processing performance, mechanical behavior, and environmental adaptability while maintaining high density and high melting point. Tungsten, as the main element, provides the material's density foundation and high-temperature stability, while binder elements such as nickel, iron, and copper are responsible for improving brittleness and promoting densification. Proportioning design is typically based on phase diagram analysis, sintering kinetics, and thermomechanical processing experiments to ensure that each element fully exerts its wetting and diffusion effects during the liquid-phase sintering stage and forms a stable two-phase structure in the solid state. Excessive tungsten content may lead to insufficient plasticity, while too much binder phase will reduce overall density; therefore, the proportions need to be adjusted according to the application scenario. For example, in applications requiring high hardness, the tungsten proportion can be appropriately increased, while in systems where thermal conductivity is important, the content of elements such as copper will be correspondingly increased. The addition of trace elements further refines the microstructure, inhibits grain growth, or improves interfacial strength, but their proportions must be strictly controlled to avoid introducing harmful phases. Overall, the role of the constituent elements is reflected in multi-scale synergy: atomic-level solid solution strengthening, micron-level phase interface regulation, and macro-level performance balance. This proportioning principle is not only applicable to traditional nickel-iron and nickel-copper systems, but can also be extended to emerging composite systems, helping materials engineers to customize alloy compositions according to specific needs.

In actual formulation, the purity and particle size distribution of tungsten powder have a significant impact on the final performance. High-purity fine powder is beneficial for uniform distribution and reducing porosity, while the binder phase elements are usually added in the form of metal powder or pre-alloyed powder to ensure uniform mixing. The selection of sintering temperature is closely related to the formulation; a higher proportion of binder phase can lower the sintering temperature, reduce energy consumption, and inhibit tungsten particle coarsening. Optimization of the formulation during heat treatment involves the design of the annealing regime, controlling the element distribution in the solid solution by regulating the cooling rate to achieve a balance between strength and toughness. The formulation also needs to be considered during surface treatment; for example, adjusting the concentration of surface elements before coating to improve adhesion. The composition of tungsten alloy

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sheets is also affected by resource availability and environmental factors; some iron or copper can be derived from recycled materials, but impurities must be controlled within acceptable limits.

3.2.1 Synergistic Mechanism of Tungsten Alloy Sheets in Nickel -Iron System

The synergistic mechanism of the nickel-iron system in tungsten alloy sheets mainly stems from the complementary behavior of nickel and iron in the binder phase and their interfacial interaction with tungsten particles. In this system, nickel, as the main binder element, provides good wettability and ductility, while the addition of iron enhances solid solution strengthening and regulates phase stability. Together, they promote the smooth progress of the liquid-phase sintering process. In the early stages of sintering, nickel and iron form a low-melting-point liquid phase, rapidly encapsulating tungsten particles, achieving particle rearrangement and initial densification. The participation of iron reduces the viscosity of the liquid phase, increases the diffusion rate, and makes it easier for tungsten atoms to dissolve in the binder phase, precipitating fine particles upon cooling, further strengthening the interface. The synergistic effect is also reflected in the microstructure evolution: the nickel-iron solid solution has a face-centered cubic structure, which can effectively absorb deformation stress and reduce direct contact between tungsten particles, thereby improving overall plasticity. During the hot working stage, this synergy makes the material less prone to crack propagation during rolling, and the microstructure recovers its uniformity after annealing.

From a chemical perspective, the difference in electronic structure between nickel and iron leads to lattice distortion in the solid solution, hindering dislocation movement and increasing the strength of the binder phase. Simultaneously, the ferromagnetism of iron affects electromagnetic properties but does not alter the non-magnetic dominance of the system. At the interface, nickel tends to form clean bonds, while iron promotes the stable presence of small oxides, jointly enhancing the interfacial energy. During cooling, the synergistic effect of both inhibits abnormal tungsten particle growth, maintaining a fine spherical morphology, which is beneficial for subsequent cold working. Microscopically, this mechanism involves a dissolution-reprecipitation mechanism: at high temperatures, tungsten partially dissolves into the nickel-iron phase, and at low temperatures, it reprecipitates and pins grain boundaries, enhancing high-temperature stability. Macroscopically, this manifests as the material maintaining dimensional stability during repeated thermal cycling, making it suitable for applications requiring resistance to thermal fatigue. Proportional control is key to the mechanism's effectiveness; the nickel-iron ratio is typically adjusted to balance wetting and strengthening effects. Excessive iron content may introduce a brittle phase, while an appropriate amount optimizes toughness.

Further analysis reveals that the synergistic effect extends to corrosion behavior: nickel provides the basis for the passivation film, while iron assists in its uniform distribution, improving corrosion resistance in acidic media. In terms of processing performance, inter-pass annealing utilizes the synergistic effect of both to restore the microstructure and reduce residual stress accumulation. Regarding environmental adaptability, this system allows for fine-tuning to cope with different humidity or temperature conditions, ensuring long-term service reliability. In summary, the synergistic mechanism of the nickel-iron system

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embodies the material science principles of inter-element complementarity and multi-scale interaction, providing a reliable foundation for the engineering applications of tungsten alloy sheets.

3.2.2 Synergistic Mechanism of Tungsten Alloy Sheet Nickel -Copper System

The synergistic mechanism of the nickel-copper system in tungsten alloy sheets is based on the infinite miscibility of nickel and copper, and the unique interfacial chemical behavior with tungsten. In this system, nickel provides bonding strength and wetting ability, while the addition of copper significantly improves thermal and electrical conductivity. Together, they form a uniform solid solution binder phase, promoting densification and microstructure optimization during sintering. During the liquid phase emergence stage, the nickel-copper liquid phase has low surface tension, easily spreading and covering tungsten particles for efficient rearrangement. The participation of copper increases the fluidity of the liquid phase, accelerates the diffusion and migration of tungsten atoms, and forms a finer interfacial layer during solidification, reducing porosity residue. The synergistic effect is reflected in thermophysical properties: the nickel-copper solid solution combines the ductility of nickel and the thermal diffusion characteristics of copper, giving the material good stability under thermal shock. During processing, this mechanism helps the material coordinate deformation during hot and cold rolling, avoiding interlayer separation.

In terms of chemical mechanisms, the similar atomic sizes of nickel and copper ensure a disordered distribution in the solid solution, resulting in slight lattice strain and increased phase strength. Simultaneously, copper's non-magnetic nature prevents the system from becoming magnetized overall, making it suitable for electromagnetically sensitive environments. In interfacial interactions, nickel tends towards chemical bonding, while copper assists in physical adsorption, together forming a low-energy interface and improving bonding durability. Regarding cooling evolution, both work synergistically to suppress uneven spheroidization of tungsten particles, maintaining microstructure consistency and facilitating the production of ultrathin sheets. At the microscale, this mechanism involves thermodynamic equilibrium: tungsten atoms dissolve at high temperatures and precipitate at low temperatures, forming dispersed reinforcing particles that enhance resistance to high-temperature creep. Macroscopically, the material maintains uniform thermal conductivity in temperature gradient environments, making it suitable for thermal management components. In terms of corrosion and weather resistance, nickel and copper synergistically promote the rapid formation of a surface passivation film, improving protection under humid or salt spray conditions. During rolling optimization, annealing utilizes the diffusion differences between the two to restore crystal defects and improve surface quality. Under environmental conditions, this system allows for fine-tuning of the proportions to adapt to different oxidation atmospheres, ensuring controllable gradual changes in material properties during long-term exposure.

3.2.3 Doping effect of trace elements on tungsten alloy sheets

Tungsten alloy sheets mainly affects the microstructure and properties of the material through grain boundary segregation, phase interface modification, and solid solution perturbation. This effect is particularly significant in traditional nickel-iron or nickel-copper systems. The addition of trace rare earth

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elements, boron, phosphorus, cobalt, etc., can refine tungsten particles, improve the toughness of the binder phase, and enhance overall uniformity. During sintering, dopants tend to accumulate in the liquid phase, reducing surface energy, promoting uniform distribution of tungsten particles, and inhibiting growth. After doping, the microstructure becomes more stable, with reduced porosity and increased density. During hot working, this effect helps reduce crack initiation, accelerates stress release during annealing, and improves yield.

Mechanistically, doping with rare earth elements such as lanthanum and yttrium forms dispersed oxide phases that pin grain boundaries, hinder migration, and increase recrystallization temperature. Boron and phosphorus form thin films at interfaces, adjusting wetting angles and enhancing interphase bonding. Cobalt doping strengthens the binder solid solution, increases stacking fault energy, and improves deformation compatibility. Microscopically, doping causes localized changes in electron density, affecting diffusion kinetics, and precipitating fine phases at low temperatures, further strengthening the material. Macroscopically, this results in a balance of mechanical properties, with coordinated fracture toughness and hardness, making it suitable for precision components.

In terms of corrosion behavior, doping elements assist in the growth of passivation films, improving resistance to media erosion. During surface treatment, doping improves coating adhesion and extends service life. In environmental adaptation, this effect allows for targeted adjustments to cope with different temperature or humidity conditions. In summary, the doping effect of trace elements embodies the material principle that small additions have a significant impact, providing an effective approach to optimizing the performance of tungsten alloy sheets. Experimental verification shows that this effect can guide emerging doping strategies and drive continuous progress in materials science.

3.3 Chemical Principles of Tungsten Alloy Sheet Composition Design

Tungsten alloy sheets primarily revolve around phase equilibrium, diffusion kinetics, and interfacial chemical behavior. These principles guide the entire process from raw material preparation to final heat treatment, ensuring the stability and repeatability of material properties. The core of composition design lies in controlling the ratio of tungsten to binder phase elements. Phase diagram analysis is used to predict potential phase structures and avoid the formation of harmful phases. For example, in the tungsten-nickel-iron system, chemical principles emphasize the balance of the nickel-iron ratio to maintain wettability during liquid-phase sintering and the stability of the solid solution after cooling. Diffusion principles require consideration of element migration rates at high temperatures. Tungsten atoms diffuse more slowly than nickel or copper, therefore, the design necessitates extending the holding time to promote uniform distribution. Interfacial chemical principles involve the binding energy between tungsten particles and the binder phase. Trace elements are often introduced in the design to adjust surface tension and improve interfacial bonding strength.

In practical design, chemical principles also include consideration of redox balance. The hydrogen dew point of the sintering atmosphere must be matched with the composition to inhibit tungsten oxidation and promote the reduction of the binder phase. During formulation, a higher tungsten content requires

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an increase in the binder phase to compensate for plasticity loss, while excessive binder phase necessitates adjustments to maintain density. The heat treatment process follows phase transformation principles, controlling the cooling rate to regulate the size and distribution of precipitated phases and optimize mechanical properties. Surface chemical principles are reflected in coating design; the composition must be compatible with the plating solution to avoid adhesion problems caused by element segregation. Under environmental considerations, principles guide the use of recycled elements, but the content of impurities such as oxygen and carbon must be controlled to prevent the introduction of brittle phases.

3.3.1 Performance-Oriented Composition Optimization Logic for Tungsten Alloy Sheets

The performance-oriented composition optimization logic for tungsten alloy sheets starts with the end-application requirements and works backward to deduce the element ratios and addition order, ensuring a coordinated balance of properties such as density, hardness, thermal conductivity, and ductility. This logic first identifies key properties; for example, when pursuing high density, it prioritizes increasing the tungsten ratio while fine-tuning the binder phase to maintain processability. The optimization process involves multiple iterations: the initial ratio is estimated based on the phase diagram to determine the liquid phase content, and adjustments are made after experimental verification to match the sintering shrinkage rate. The logic emphasizes synergy between elements; for example, nickel provides ductility, while iron or copper supplements strengthening or thermal conductivity, and optimizing their ratio can improve thermal stability. Micro-doping serves as a fine-tuning method; rare earth elements refine the microstructure, and boron and phosphorus adjust the interface to improve corrosion resistance.

The logic also includes considerations of performance trade-offs. For high hardness, the tungsten content is increased and carbides are added, but the decrease in toughness must be monitored, and the balance is restored through annealing optimization. For thermal conductivity, the copper ratio is increased, but the proportion must avoid excessive liquid phase leading to a porous microstructure. In optimization, chemical simulation tools assist in predicting phase formation paths, helping to reduce experimental cycles. Thermomechanical processing feedback is incorporated into the logic; rolling defect analysis guides fine-tuning of the composition, such as adding cobalt to improve deformation coordination. For environmental performance, optimization focuses on the formation of corrosion-resistant phases, and the addition ratio of chromium or molybdenum is adjusted according to the type of medium. The overall logic forms a closed loop: requirement definition - proportion design - preparation verification - performance testing - iterative adjustment, ensuring a close correlation between composition and performance. Through this logic, tungsten alloy sheets can adapt to diverse requirements in fields such as precision instruments and thermal management, demonstrating the practical orientation of material design.

3.3.2 Chemical control methods for the compositional uniformity of tungsten alloy sheets

Chemical control of the compositional uniformity of tungsten alloy sheets is mainly achieved through powder mixing, sintering parameter adjustment, and heat treatment diffusion. These methods ensure

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quality control at every stage from the source to the finished product, avoiding performance fluctuations caused by segregation and inhomogeneity. In the powder mixing stage, methods include mechanical alloying or spray drying to ensure uniform distribution of elements such as tungsten, nickel, and iron at the micron scale. Chemical additives, such as surfactants, assist in powder dispersion. In sintering control, liquid phase quantity regulation is crucial. Temperature gradient design promotes uniform wetting, and hydrogen flow removes volatile impurities, reducing local enrichment. Cooling rate adjustment suppresses uneven element diffusion, and rapid cooling locks in a uniform state.

Heat treatment methods involve vacuum annealing to promote atomic-level diffusion, eliminate concentration gradients, and further homogenize the material through multiple annealing cycles. Surface chemical methods, such as ion implantation or chemical vapor deposition, introduce a uniform layer on the sheet surface, improving overall consistency. In quality control, chemical analysis feedback guides method iteration, for example, adjusting the proportions after detecting segregation areas using spectroscopy. Environmentally friendly methods use pre-alloyed powders to reduce the risk of uneven mixing.

3.3.3 Influence of Impurity Elements on the Performance of Tungsten Alloy Sheets

Impurities in tungsten alloy sheets mainly originate from raw tungsten powder, binder phase powder, gases introduced during processing, and equipment residues. Even extremely low levels can significantly affect the microstructure, mechanical behavior, and environmental adaptability. Common impurities include oxygen, carbon, nitrogen, phosphorus, sulfur, silicon, potassium, sodium, and calcium, with oxygen and carbon having the most widespread impact.

When oxygen exists in free or oxide form, it readily forms a thin oxide film on the surface of tungsten particles, reducing wettability during liquid-phase sintering, weakening interfacial bonding, and causing localized micropores or inclusions. This, in turn, reduces fracture toughness and increases the tendency for rolling cracking. Oxygen also reacts with tungsten at high temperatures to form volatile oxides, roughening the surface of tungsten particles, hindering particle rearrangement, and affecting the final density. The presence of carbon is more complex: trace amounts of carbon can form fine carbides with tungsten, providing some dispersion strengthening, but excessive carbon will segregate at grain boundaries or interfaces, forming brittle WC or W_2C , significantly weakening interfacial strength and increasing the tendency for intergranular fracture under stress. Nitrogen is usually reduced and removed under high-temperature hydrogen atmospheres, but residual nitrogen will form nitride needle-like phases with tungsten, also becoming crack initiation sites. Even trace amounts of elements such as phosphorus and sulfur easily accumulate in the binder phase or at the interface, forming low-melting-point compounds, reducing high-temperature strength and inducing hot embrittlement. Alkali metals such as potassium and sodium, as well as calcium and silicon, mainly originate from residues in the tungstate process for preparing tungsten powder. They volatilize or form pores during sintering, disrupting the continuity of the structure and causing bubbling or delamination in severe cases.

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Impurities also have a synergistic effect on performance. For example, the coexistence of oxygen and phosphorus makes it easier to form a phosphate glass phase, which encapsulates tungsten particles, hinders the dissolution-re-precipitation process, and causes irregular shapes of tungsten particles, reducing their sphericity. During high-temperature service, areas enriched with impurities often become preferential sites for oxidation or corrosion, accelerating material failure. In the production of ultra-thin sheets, minute defects caused by impurities can be amplified, becoming the starting point for edge cracks or orange peel-like surface defects. Therefore, modern tungsten alloy sheet production places increasingly higher demands on raw material purity and process cleanliness, and impurity control has become one of the key factors determining whether a material can enter high-end applications.

3.3.4 Methods for removing impurity elements from tungsten alloy sheets

Tungsten alloy sheets is carried out throughout the entire process chain from raw material preparation to finished product heat treatment. It comprehensively adopts a variety of methods such as chemical purification, physical refining, atmosphere purification and post-treatment to form a multi-stage purification system.

The removal process at the raw material stage is of paramount importance. Tungsten powder typically uses high-purity ammonium tungstate as a precursor, and through multiple recrystallization and deep hydrogen reduction processes, impurities such as oxygen, alkali metals, and phosphorus are reduced to low levels. Binder phase nickel, iron, and copper powders are prepared using carbonyl or electrolytic methods, followed by vacuum degassing to further reduce carbon, oxygen, and sulfur content. Before mixing, tungsten powder often undergoes a secondary high-temperature hydrogen purification treatment, utilizing the reduction reaction of hydrogen with oxides to generate water vapor, which is then discharged, simultaneously carrying away residual volatile impurities such as potassium and sodium.

The sintering stage is a critical window for removing gaseous and volatile impurities. A wet hydrogen atmosphere (with strictly controlled dew point) efficiently reduces oxides on the surface of tungsten particles and carries water vapor out of the furnace; dry hydrogen or high-vacuum sintering is used to remove nitrogen and residual hydrocarbons. To prevent the re-condensation of low-melting-point impurities such as phosphorus and sulfur after volatilization, a staged heating process is often employed, first completing degassing at a lower temperature and then rapidly raising the temperature to the liquid-phase sintering temperature. The insulating pad between the furnace charge and the billet must be made of high-purity graphite or alumina to avoid secondary contamination.

Removal during hot working and heat treatment primarily relies on high vacuum or high-purity flowing hydrogen. Preheating before hot rolling or warm rolling is carried out in a vacuum furnace to further volatilize residual alkali metals; multiple intermediate annealings after cold rolling are also completed under high vacuum conditions, allowing residual gases to escape through diffusion. In the production of ultra-thin foils, a dedicated vacuum degassing annealing process is often added to ensure that there are no micropores in the thickness direction.

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Post-treatment removal targets surface or near-surface impurities. Chemical pickling can selectively dissolve oxygen-rich and phosphorus-rich layers on the surface ; electropolishing or plasma cleaning can effectively remove adsorbed organic matter and metal ions; vacuum heat treatment with titanium getters can deeply capture residual oxygen and nitrogen. Some high-end sheets also use zone melting refining or electron beam melting for final purification of the billet.

In summary, impurity removal in tungsten alloy sheets follows a three-tiered strategy: "source control—process elimination—finished product refining." Through the synergistic effect of multiple methods, oxygen content can be stably controlled within an extremely low range, and other harmful impurities are also significantly reduced, thus laying the foundation for the material's high reliability and long lifespan.



CTIA GROUP LTD Tungsten Alloy Sheets

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Chapter 4 The Relationship Between the Structure and Properties of Tungsten Alloy Sheets

4.1 Microstructure of tungsten alloy sheet

The microstructure of [tungsten alloy sheets](#) typically exhibits a two-phase composite characteristic, with tungsten particles as the hard phase, encapsulated by nickel-based or copper-based binder phases, forming a cermet-like microstructure. This structure originates from powder metallurgy and further evolves after sintering through thermomechanical processing. Tungsten particles are mostly near-spherical or polyhedral, and their size distribution affects structural uniformity. The binder phase fills the interparticle gaps, providing continuous deformation channels. Defects such as porosity and dislocations are unavoidable in the structure but can be minimized through process control. The microstructure also includes interface layers, where transition zones formed by element diffusion enhance interphase bonding. Observational methods such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) reveal structural details, aiding in the analysis of the origin of properties. Structural evolution varies with processing stages; particles spheroidize during sintering and become fibrous during rolling.

4.1.1 Grain structure and grain boundary chemical composition

Tungsten alloy sheets mainly consists of body-centered cubic (BCC) crystals of the tungsten phase and face-centered cubic (FCC) crystals of the binder phase. The former occupies the main volume, providing the basis for high hardness and density, while the latter acts as a continuous matrix, improving overall plasticity. During sintering, tungsten grains gradually spheroidize through a dissolution-reprecipitation mechanism. Initially polygonal particles tend to have uniform surface curvature under the influence of the liquid phase, eventually forming aggregates of relatively uniform size. This structural evolution is influenced by the wettability of the binder phase; good wetting promotes particle rearrangement, reduces contact angles, and forms low-energy grain boundaries. Grain size is usually controlled by powder particle size and sintering temperature. Fine powder and long holding time are beneficial for small grain structures, improving strength but potentially reducing ductility. Rolling introduces deformation-induced recrystallization, elongating the grains along the rolling direction and forming fibrous textures, further optimizing anisotropic properties.

Grain boundary chemical composition plays a crucial role in tungsten alloy sheets, primarily involving the elemental distribution at the tungsten-binder phase interface. The interface often accumulates small amounts of tungsten atoms, which precipitate from the binder phase, forming a thin solid solution region that enhances bonding strength. In nickel-iron systems, iron tends to segregate at grain boundaries, regulating electron density and influencing dislocation movement paths. Copper systems exhibit a uniform distribution of copper at the interface, promoting the continuity of thermal conductivity channels. Trace impurities such as oxygen and phosphorus accumulate at grain boundaries, potentially forming compound films that alter boundary energies; these must be controlled through purification processes to avoid embrittlement. Chemical composition analysis commonly utilizes energy dispersive spectroscopy

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(EDS) or atomic probe microanalysis to reveal gradient changes at the interface. This gradient helps buffer stress and reduce crack propagation.

Furthermore, the stability of grain structure is closely related to grain boundary composition. High-vacuum sintering can suppress the formation of oxygen oxides at the interface, maintain a clean interface, and improve high-temperature service reliability. Annealing adjusts the composition through diffusion, dilutes segregating elements, and restores structural balance. Grain boundary types are diverse; large-angle boundaries facilitate element migration, while small-angle boundaries are more stable. Processing parameters such as reduction affect boundary density; high-density boundaries can pin dislocations and increase hardness. When exposed to the environment, grain boundary composition determines the corrosion path, and the enrichment of passivating elements can form a protective film.

4.1.2 Distribution and Chemical State of Alloy Phases

The alloying phases in tungsten alloy sheets mainly include tungsten solid solution phases and binder solid solutions. The former consists of alloying elements with limited dissolution within the tungsten grains, while the latter consists of tungsten atoms dissolved in a nickel-based or copper-based matrix. In terms of distribution, the tungsten phase is uniformly embedded in the binder phase as discrete particles, forming a composite network. The particle spacing is determined by the volume ratio of the binder phase; smaller spacing is beneficial for uniform stress transfer. Chemically, the tungsten phase maintains a high purity state, and a thin oxide or solid solution transition zone may exist on the surface. The binder phase has a more complex chemical state. In the nickel-iron system, it is a γ -phase solid solution, where iron atoms replace some nickel positions, forming a disordered arrangement. This state is stable, but an ordered phase may precipitate with temperature changes. The copper system is similar; copper and nickel are infinitely miscible, ensuring a uniform state and no tendency for phase separation.

Phase distribution optimization depends on sintering kinetics. Particle rearrangement in the liquid phase leads to a more random distribution, preventing agglomeration. Heat treatment further homogenizes the distribution; diffusion-driven particle boundary adjustment reduces local density differences. Chemical state is affected by cooling rate; rapid cooling locks in a supersaturated state, while slow cooling promotes precipitation, forming fine, reinforcing phases. The chemical state at the interface is unique, with elemental gradient regions present; tungsten gradually transitions from particles to the binder phase, enhancing compatibility. Observational techniques such as X-ray diffraction confirm the state, showing no harmful compound peaks. Uneven distribution can lead to performance gradients, requiring initial homogeneity control through stirring and mixing. During annealing, state evolution includes recrystallization, reducing crystal defects and improving conductivity.

Furthermore, the interaction between phase distribution and state influences environmental behavior. A uniformly distributed binder phase provides continuous protection, while a chemically stable state resists oxidation. During processing, rolling and stretching distribute the phase, forming an oriented structure. The state is maintained, but strain induces dislocation accumulation.

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4.1.3 Chemical Origin Analysis of Defect Structures

Tungsten alloy sheets mainly include point defects, line defects, surface defects, and volume defects. Their chemical origins stem from uneven element diffusion, interphase reactions, and the introduction of impurities. Point defects, such as vacancies and interstitial atoms, are often generated by the dissolution and precipitation of tungsten atoms in the binder phase during sintering; supersaturated tungsten leads to an increased vacancy concentration. Line defects, i.e., dislocations, are related to rolling deformation; solid solution strengthening in the binder phase increases dislocation density, and chemically, iron or copper atoms pin dislocations, affecting their movement. Surface defects, such as grain boundaries and phase boundaries, are chemically caused by impurity segregation; oxygen and phosphorus accumulate at the interface to form compounds, altering their energy states. Volume defects, such as porosity and inclusions, are caused by incomplete sintering, resulting from residual gases or unremoved oxides.

The analysis revealed that defect formation is also driven by thermodynamics: high-temperature diffusion promotes vacancy migration, while low-temperature freezing forms clusters. Impurities have a significant chemical effect, with carbon and nitrogen forming interstitial compounds that increase defect volume. Annealing reduces defects, heals vacancies through diffusion, and redistributes impurities under chemical equilibrium. Interface defects have unique causes: thermal expansion differences induce microcracks, and elemental gradients alleviate stress. Observational methods, such as electron microscopy, reveal the causes, while energy-dispersive X-ray spectroscopy shows impurity correlations. The impact of defects on performance needs to be controlled; chemical purification reduces the intensity of their formation.

4.2 Properties and Mechanisms of Tungsten Alloy Sheets

Tungsten alloy sheets mainly stem from the unique design of their composite structure. The interaction between the tungsten phase and the binder phase achieves various aspects such as density, thermal conductivity, and thermal stability. The performance mechanism involves chemical processes such as atomic-level packing, electron transport, and interphase support. For example, high density originates from the close arrangement of tungsten atoms, while thermal and electrical conductivity depend on the migration paths of free electrons. The thermal stability mechanism is based on the thermodynamic equilibrium of the phase structure, with interfacial bonding inhibiting high-temperature deformation. Mechanistic analysis helps understand the origin of performance, such as how the rolling process affects electron scattering, thereby regulating conductivity. Under environmental factors, the mechanism also includes oxidation behavior, where the surface chemical state affects stability.

4.2.1 The principle of high-density chemical atom packing in tungsten alloy sheets

The high-density chemical atomic packing principle of tungsten alloy sheets is mainly based on the high atomic mass of tungsten atoms and the compact arrangement of their body-centered cubic crystal structure. This structure allows atoms to efficiently fill a limited space, and the alloying process further optimizes the packing method. Through powder metallurgy, tungsten powder undergoes particle

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rearrangement during sintering, and the liquid-phase binder promotes the proximity of tungsten atoms, forming a dense network. The principle of atomic packing involves the synergy of van der Waals forces and metallic bonds. Tungsten atoms have a relatively large radius but a moderate lattice constant, ensuring minimal interatomic gaps within the body-centered cubic unit. The addition of alloying elements such as nickel and iron does not directly change the packing of the tungsten phase, but adjusts the overall volume through solid solution formation, reducing vacancy defects.

The stacking principle is also reflected in the interphase interaction. The binder phase atoms fill the gaps between tungsten particles, similar to a liquid wetting a solid surface, and chemical bonding enhances the connection strength. In sintering kinetics, surface energy drives atomic migration, and tungsten surface atoms diffuse into the recessed areas, achieving smooth stacking. During cooling, thermal contraction further compresses the interatomic spacing, and precipitated phases under chemical equilibrium help lock the structure. Microscopically, this principle manifests as the orderliness of the tungsten lattice; substitutional solid solution restricts lattice expansion, maintaining a high fill factor. In macroscopic performance, the high density stems from this atomically compactness, making it suitable for applications requiring concentrated mass.

Further analysis reveals that the packing principle is influenced by the electronegativity of the elements. The electronegativity difference between tungsten and the binder phase elements promotes electron sharing, forming a stable bond network. The unique atomic packing at the interface, with its gradient region, allows tungsten atoms to gradually integrate into the binder phase, improving overall coherence. Process parameters such as temperature gradients control the packing process, while high temperatures extend diffusion time and optimize filling uniformity. Impurity elements interfere; compounds formed by oxygen and other elements occupy space and must be removed using a reducing atmosphere. Annealing restores the packing order, and diffusion heals voids. In environmental adaptation, this principle ensures relatively stable density under temperature changes, supporting long-term use.

4.2.2 Chemical carrier mechanism for the thermal and electrical conductivity of tungsten alloy sheets

Tungsten alloy sheets mainly relies on the transport of free electrons and phonons. The tungsten phase provides high electron density, while the binder phase optimizes the transport path, forming a composite carrier system. The conductivity mechanism involves electron sharing within the metallic bonds; outer electrons of tungsten atoms readily detach, forming an electron gas, and the introduction of nickel or copper atoms through alloying increases the carrier concentration. Thermal conductivity is achieved through phonon vibrations, with lattice vibrations propagating efficiently in the tungsten phase and the binder phase buffering scattering. The chemical basis of this mechanism lies in the valence electron configuration; the d-electron layer of tungsten hybridizes with the sp-electrons of the binder phase, enhancing carrier mobility.

The carrier mechanism is also reflected in the phase distribution; the continuous bonded phase forms a conductive network, reducing interfacial resistance, and the chemical stability ensures unimpeded

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electron flow. The sintering process optimizes the mechanism, with the liquid phase promoting a clean interface and lowering the potential barrier. While cooled precipitates may scatter carriers, appropriate strengthening actually improves thermal conductivity. Microscopically, the mechanism involves the Fermi surface shape; alloying elements adjust the electronic structure, affecting the effective mass of carriers. In macroscopic performance, this mechanism supports thermal management and electronic applications, achieving a balance between thermal and electrical conductivity.

Furthermore, the mechanism is influenced by defect chemistry, with dislocations or vacancies scattering carriers, which needs to be reduced through annealing. Impurity elements such as oxygen form traps, capturing electrons and reducing conductivity; purification processes mitigate this effect. In temperature dependence, the mechanism shows electron-phonon coupling; high temperatures increase scattering, but the stability of the tungsten phase remains at a basic level. Surface chemical states affect the mechanism; oxide layers block carriers, while coatings protect and restore performance. During processing, rolling induces texture, and orientation mechanisms improve anisotropic conductivity. Under environmental factors, corrosion alters the carrier path, and passivation films assist in maintenance.

4.2.3 Chemical Structure Supporting the Thermal Stability of Tungsten Alloy Sheets

Tungsten alloy sheets primarily stems from the thermodynamic equilibrium of the two-phase structure. The high melting point of the tungsten phase provides skeletal support, while the solid solution of the binder phase regulates stress distribution and suppresses high-temperature deformation. The chemical principle of structural support involves interphase bonding, with a mixture of metallic and covalent components ensuring the bond network does not disintegrate at high temperatures. The interface layer formed during sintering creates a gradient structure through elemental diffusion, buffering thermal expansion differences and maintaining overall integrity. The cooling process locks in the support, and precipitated phases pin grain boundaries, hindering migration.

The support mechanism is also reflected in the microstructure stability: spheroidization of tungsten particles reduces stress concentration, and the uniform distribution of the binder phase disperses the thermal load. Chemically, solid solution strengthening increases the phase melting point, while alloying elements adjust free energy and reduce the driving force of phase transformation. Microscopically, the support involves harmonious atomic vibrations and coordinated phonon modes between phases, preventing localized softening. In macroscopic performance, this support supports high-temperature applications, and its stability is demonstrated during cyclic heating.

Further analysis reveals that the mechanism is influenced by oxidation chemistry, forming a protective film on the surface to block oxygen diffusion while maintaining the internal structure. Impurities interfere with the support structure; phosphorus and other elements induce brittle phases, which are eliminated by high-purity processes. Annealing optimizes the support structure, diffusion adjusts the composition, and restores equilibrium. In a temperature gradient, the support exhibits a gradual response, with the tungsten phase dominating in the low-temperature region and the binder phase assisting in the high-temperature region. Processing history also influences the mechanism; previous deformation introduces a dislocation

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network, enhancing high-temperature strength. During environmental exposure, corrosion tests demonstrate the support's reliability, and the chemically inert phase extends its lifespan.

4.3 Correlation between mechanical and chemical properties of tungsten alloy sheets

Tungsten alloy sheets is mainly reflected in how the material's microstructure influences macroscopic behavior through chemical bonding and elemental distribution. This correlation helps in understanding the origins of properties such as hardness, wear resistance, and corrosion resistance. Mechanical properties, such as strength and toughness, often stem from lattice arrangement and interphase interactions, while chemical properties, such as corrosion resistance, involve surface reactions and elemental electrochemical behavior. These two are closely linked through interfacial chemistry. For example, the hard framework of the tungsten phase provides mechanical support, while the solid solution of the binder phase modulates chemical stability, together forming a performance balance. The correlation mechanism includes the contribution of atomic-level bond strength; metallic bonds dominate hardness in the tungsten phase, while covalent components enhance bonding at the interface, affecting deformation resistance. Chemical reactions during sintering shape the structure, the liquid phase promotes elemental diffusion, forming gradient regions, mechanically reducing stress concentration and chemically enhancing oxidation resistance.

Heat treatment further strengthens the correlation; annealing adjusts element positions through diffusion, optimizing mechanical plasticity and chemical inertness. Under environmental factors, the correlation manifests as a synergistic response in performance; humidity or acidic media can simultaneously weaken mechanical integrity and the chemical protective layer. Processing history affects the correlation; the dislocation network introduced by rolling increases strength mechanically and alters electron distribution chemically, influencing corrosion potential. The role of impurity elements cannot be ignored; the segregation of oxygen or phosphorus forms weak bond regions chemically and becomes crack initiation sites mechanically, requiring purification to mitigate these effects.

4.3.1 Relationship between hardness and chemical bond strength of tungsten alloy sheets

Tungsten alloy sheets and the strength of chemical bonds is based on the diversity and strength distribution of bonding types within the material. This relationship reflects how the interaction between the tungsten phase and the binder phase jointly contributes to the material's resistance to deformation. Hardness, as a mechanical indicator, originates from the strength of interatomic interactions, while the strength of chemical bonds is influenced by bond energy and the degree of electron sharing. In tungsten alloy sheets, the body-centered cubic structure of the tungsten phase is dominated by metallic bonds, which have high bond strength and provide basic hardness. The face-centered cubic solid solution of the binder phase introduces more covalent components, regulating the overall bond network. The core of the relationship lies in the mixing of bonds at the interface. The bonding of tungsten atoms with nickel or iron forms a transition region with a gradient distribution of bond strength, helping to buffer external loads.

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The enhancement of chemical bond strength is often achieved through solid solution strengthening. Alloying elements dissolve into the crystal lattice, causing distortion and increasing the resistance to dislocation movement, thus improving hardness. Within the tungsten phase, bond strength depends on purity; in a high-purity state, metallic bonds are uniformly distributed, resulting in stable hardness. The introduction of impurities weakens the bonds, forming localized soft regions. In the binder phase, nickel-iron intermingling enhances bond strength, and iron atoms adjust electron cloud density, promoting bond stability. The sintering process affects this relationship; bond recombination occurs in the liquid phase, and precipitates further strengthen the bond network during cooling, leading to changes in hardness. Rolling deformation induces bond strain, chemically enriching dislocations with surrounding elements, increasing localized hardness, but requires annealing for equilibrium.

The relationship extends to temperature dependence; at high temperatures, bond vibrations increase, leading to a decrease in hardness. However, the bond strength of the tungsten phase remains relatively stable, supporting applications in thermal environments. Surface chemical bond strength affects hardness testing; oxide layers form weak bonds, requiring protective coatings to restore them. The addition of impurities such as carbon can form carbide bonds, which are strong but require uniform distribution to avoid embrittlement. Under environmental factors, humidity promotes hydrogen bonding, weakening surface bonds and indirectly reducing hardness.

4.3.2 Chemical Corrosion Resistance Mechanism of Tungsten Alloy Sheets

Tungsten alloy sheets primarily stems from the composite design of the material structure and the synergy of surface chemical reactions. This mechanism helps the material maintain its integrity under friction and media action. Wear resistance, as a mechanical property, involves a balance between surface hardness and toughness, while chemical corrosion resistance inhibits erosion through passivation films and elemental electrochemical behavior; the two interact to form a protective system. In tungsten alloy sheets, the tungsten phase provides the wear-resistant framework, the binder phase modulates chemical activity, and the elemental distribution at the interface optimizes the resistance mechanism. The core of the mechanism lies in the chemical transformation during friction; surface atoms rearrange under stress to form an oxide layer or adsorption film, reducing the wear rate.

Corrosion resistance mechanisms are achieved through electrochemical passivation, where nickel or copper promotes the formation of a stable oxide film on the surface, blocking media penetration. Mechanically, film adhesion depends on bond strength. In wear environments, the mechanism involves the coupling of oxidative and corrosive wear; chemical reactions generate protective products, mechanically reducing the coefficient of friction. Sintering processes shape the structure, with the liquid phase promoting a uniform microstructure and reducing corrosion-sensitive areas. Surface texture after rolling affects the mechanism, chemically smoothing the surface reduces media retention and mechanically distributing stress evenly. Impurity element interference mechanisms include phosphorus and sulfur enrichment inducing localized corrosion, requiring purification and control.

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The mechanism exhibits a significant temperature dependence; oxidation accelerates at high temperatures, but the stability of the tungsten phase remains resistant. Coating treatments enhance the mechanism; electroless nickel plating forms an additional barrier, improving wear resistance. Environmental media such as acids and alkalis alter the mechanism, and the adaptability of the passivation film determines long-term performance.

4.3.3 The surface chemical barrier effect of tungsten alloy sheets on corrosion resistance

Tungsten alloy sheets in achieving corrosion resistance is primarily based on the formation of oxide films and adsorption layers. This function maintains material stability by preventing contact between the medium and the substrate. Corrosion resistance, as a chemical property, originates from the electrochemical behavior of surface elements, while the barrier effect involves the construction of a multilayer structure. Mechanically, the film layer must possess adhesion to resist peeling. In tungsten alloy sheets, the tungsten phase surface is easily oxidized to form a WO_3 layer, but binder elements such as nickel promote the formation of a composite film, enhancing the barrier effect. The underlying principle is thermodynamic stability and low film free energy, which inhibits further reactions.

The barrier effect is achieved through self-passivation; the film self-heals after initial oxidation, and its chemical composition includes nickel or copper oxide. Mechanically, the film's flexibility prevents cracking. The surface condition after sintering influences the barrier's performance; a clean surface facilitates uniform film formation. Surface roughness during rolling controls the barrier's effectiveness, and chemically, micro-textures increase adhesion points. The initial content of impurities, such as oxygen, determines the barrier's quality; excessive oxygen leads to a porous film. Under environmental conditions, the barrier adapts to different media; under acidic conditions, the film dissolves and reconstructs. Furthermore, temperature significantly affects the barrier's performance; high temperatures accelerate diffusion but maintain the composite film's stability and barrier function. Coating technology extends the barrier's effectiveness; vacuum chromium plating forms an additional layer, enhancing overall resistance.

4.4 Process-Structure-Performance Correlation Analysis of Tungsten Alloy Sheets

The process-structure-performance correlation analysis of tungsten alloy sheets focuses on the logical chain from preparation to final performance. This analysis helps to understand how process parameters can control the microstructure, thereby affecting macroscopic behavior. Process steps such as sintering, rolling, and surface treatment each act at different scales: sintering establishes the initial structure, rolling further optimizes deformation, and surface treatment targets the chemical interface. Structure, acting as an intermediary, includes grain distribution, interphase bonding, and defect states; these elements are linked to performance through chemical bonding and element diffusion. Performance encompasses mechanical, thermal, and chemical aspects; for example, hardness stems from lattice strength, and corrosion resistance depends on surface barriers. The correlation manifests as multi-level conduction: processes alter atomic arrangement, structure adjusts the bond network, and performance responds accordingly. The analytical framework emphasizes feedback loops; performance test results guide

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process adjustments, ensuring the material's suitability for industrial applications. Through this analysis, the design of tungsten alloy sheets becomes more systematic, supporting their use in precision fields.

In practical analysis, correlation also involves the balance of thermodynamics and kinetics. Process temperature affects the diffusion rate, and structural stability determines performance durability. Elemental ratios play a bridging role in correlation; high tungsten content results in a dense structure and performance biased towards high density, but requires process compensation for plasticity. Environmental factors are incorporated into the analysis; humidity or temperature changes test the robustness of the correlation. Impurity control is maintained throughout the entire process, and chemical purification prevents defect amplification from affecting performance.

4.4.1 The effect of sintering process on the microstructure of tungsten alloy sheets

The sintering process regulates the microstructure of tungsten alloy sheets primarily through parameters such as temperature, atmosphere, and time, controlling phase formation, particle evolution, and interfacial bonding. This regulation lays the foundation for subsequent material processing and performance. During sintering, the powder mixture undergoes a transformation from solid-phase diffusion to liquid-phase formation. Tungsten particles rearrange themselves under the wetting of the binder phase, forming a uniformly distributed biphasic structure. Temperature control is crucial; high temperatures promote liquid phase formation, and binder elements such as nickel or copper melt and encapsulate the tungsten particles, chemically reducing surface energy and promoting particle spheroidization. Lower temperatures are used for solid-phase sintering to avoid excessive liquid phase leading to a porous structure. The atmosphere also influences control; hydrogen reduces oxides, maintaining a clean interface, while nitrogen or vacuum suppresses porosity caused by residual gas. Time parameters allow for sufficient diffusion; prolonged holding time promotes limited dissolution of tungsten atoms in the binder phase, and subsequent cooling precipitates fine phases, strengthening the structure.

The regulatory effect is also reflected in the adjustment of grain size. Rapid heating can retain fine particles, while a slow process allows for growth. The chemical mechanism involves Ostwald ripening, where larger particles engulf smaller ones, achieving uniform size. Phase distribution is controlled through proportioning; as the proportion of the binder phase increases, the structure tends towards a continuous network, improving coherence. Interfacial chemistry gradually forms during sintering, elemental gradient regions appear, and the interdiffusion of tungsten and nickel creates a transition layer, enhancing bonding. Defect control is a key focus; porosity is reduced through liquid-phase filling, dislocations recover at high temperatures, and chemical impurities volatilize and are expelled, preventing agglomeration. The sintered structure provides a basis for rolling; the uniform microstructure facilitates deformation without cracking.

Furthermore, the regulatory effect extends to the heat treatment stage. Post-sintering annealing further homogenizes the structure, diffuses and adjusts the positions of elements, and optimizes grain boundary composition. Combinations of process parameters allow for targeted regulation; for example, when

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pursuing a fine-grained structure, lower temperatures and longer holding times are used to chemically inhibit grain boundary migration. Atmosphere purity affects the regulatory effect; a high-purity environment reduces oxide inclusions and maintains structural integrity. The treatment of impurity elements is reflected in sintering; phosphorus and sulfur are removed through volatilization, and low residual amounts result in structural stability. In terms of environmental adaptability, this regulation ensures that the structure remains relatively stable under temperature changes, making it suitable for thermal cycling applications.

4.4.2 The Influence Mechanism of Rolling Process on the Mechanical Properties of Tungsten Alloy Sheets

The rolling process affects the mechanical properties of tungsten alloy sheets primarily through deformation-induced structural changes, regulating strength, toughness, and hardness. This mechanism involves multi-level interactions, including dislocation accumulation, grain refinement, and interphase coordination. During rolling, whether hot or cold rolling, the tungsten phase bears the main stress, while the binder phase assists in deformation flow, leading to chemical bond network reconstruction, increased dislocation density, and improved yield strength. Hot rolling, with its higher temperature, causes dynamic recovery, where diffusion promotes crystal defect healing and prevents brittleness. Cold rolling introduces more work hardening, involving slip system activation, elongation of tungsten particles along the rolling direction, forming fibrous texture, and improved tensile properties.

The influencing mechanism is also reflected in toughness adjustment. Multi-pass rolling accompanied by intermediate annealing allows chemical diffusion to adjust stress distribution and reduce the tendency for cracking caused by residual stress. The reduction control mechanism is crucial; large reductions induce recrystallization nuclei, refine grains, and improve the balance between strength and toughness. In the interphase mechanism, the binder phase acts as a buffer layer, absorbing deformation energy, and the chemical bonding strength determines the coordination efficiency. Defect evolution is also a mechanism component; rolling generates dislocation walls, and chemically, element segregation and pinning stabilize the structure. Surface effects are also reflected in the mechanism; rolling finish affects fatigue performance and chemically reduces oxidation initiation points.

Further analysis reveals a significant temperature dependence of the mechanism, combining the advantages of warm rolling with hot rolling. The mechanism exhibits both recovery and hardening, optimizing mechanical properties. Process parameters such as rolling speed influence the mechanism, rapidly reducing recovery time and increasing hardness. Impurity elements interfere with the mechanism; oxygen and other elements induce cracks, requiring prior purification to mitigate these effects.

4.4.3 Optimization Path of Surface Treatment on the Chemical Properties of Tungsten Alloy Sheets

Surface treatment optimizes the chemical properties of tungsten alloy sheets primarily through methods such as plating, oxidation, or chemical modification to create a protective interface. This approach enhances chemical behaviors such as corrosion resistance, oxidation resistance, and affinity. The process

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involves surface cleaning followed by film deposition, forming a new chemical phase layer that blocks media intrusion. Electroplating is common, where nickel or gold layers are deposited electrochemically, optimizing the formation of a dense film through ion reduction, with adhesion dependent on matrix element diffusion. Vacuum plating is used in high-temperature environments, where evaporative aluminum deposition forms an alumina barrier, resulting in high chemical stability. Chemical polishing removes surface defects; under acidic conditions, the tungsten phase is slightly dissolved, smoothing the interface and improving chemical inertness.

The optimization pathway also includes composite treatments, post-coating thermal diffusion, enhanced chemical bonding, and elemental interpenetration within the pathway to form gradient regions, improving adhesion. The ion implantation pathway introduces nitrogen or carbon, hardening the surface while optimizing chemistry; the mechanism involves atomic embedding into the crystal lattice, altering the electronic structure, and improving dielectric resistance. The anodic oxidation pathway generates an oxide film; under electrolytic conditions, a tungsten oxide layer is self-generated; the pathway controls voltage to adjust thickness; and the chemically passivating film layer passivates the substrate. Cleaning pretreatment is fundamental to the pathway; ultrasonic or plasma treatment removes contaminants to ensure uniform subsequent adhesion.

Furthermore, temperature control is crucial in the coating path; low-temperature treatment preserves the substrate structure, while high-temperature diffusion optimizes the interface. Impurities affect the coating path, and surface residues interfere with film formation, requiring multi-step cleaning to mitigate this. Environmentally adaptable coating paths involve selecting specific coatings for acidic and alkaline media, with chemical compatibility determining the effectiveness. Post-annealing treatment further stabilizes the film layer, ensuring uniform diffusion and improving long-term chemical performance.

4.5 Structural and performance response of tungsten alloy sheets under special environments

Tungsten alloy sheets under special environments primarily reflect the material's adaptation to external conditions. This response involves the evolution of microstructure and the adjustment of macroscopic behavior, helping to understand how materials maintain their function under conditions such as high temperature, radiation, or pressure. Structural responses include grain changes, interphase interactions, and defect dynamics, while performance responses are reflected in mechanical, thermal, and chemical aspects, such as thermal stability at high temperatures, chemical resistance under radiation, and mechanical evolution under pressure. The response mechanism stems from the balance between the elasticity of chemical bonds and the phase structure; the tungsten phase provides skeletal support, while the binder phase modulates the buffer. The superposition of environmental factors complicates the response; increased temperature may induce diffusion, radiation affects electronic structure, and pressure alters interatomic spacing. Correlation analysis emphasizes a multi-scale perspective, from atomic-level bond reconstruction to macroscopic performance degradation. Process pretreatments such as alloy optimization can improve responsiveness, and elemental ratio adjustments help the structure gradually stabilize in the environment.

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In practical responses, the interaction between structure and performance forms a feedback loop. The initial structure determines the response starting point, while subsequent evolution affects performance durability. The role of impurity elements needs to be considered; oxygen, for example, may accelerate negative changes in the response, which can be mitigated through purification. With gradual changes in temperature gradient or radiation dose, the response exhibits nonlinearity, stabilizing early and accelerating later. Pressure responses involve volumetric compression, and the compression of chemical bonds enhances strength.

4.5.1 Changes in the structural stability of tungsten alloy sheets under high temperature conditions

Tungsten alloy sheets at high temperatures mainly stem from thermally activated diffusion processes and the coordination of interphase thermal expansion. These changes affect the overall integrity and functional continuity of the material. At high temperatures, the body-centered cubic lattice of the tungsten phase remains relatively stable, but atomic migration begins in the solid solution of the binder phase. Tungsten atoms dissolve from the particle edges into the binder phase, forming a supersaturated state. With increasing temperature, this dissolution intensifies, changing the surface curvature of the particles, leading to a gradual shrinkage of small particles and a slight increase in the size of large particles, resulting in a coarsening structure. The mechanism involves interfacial chemistry; thermal energy drives elemental diffusion, with nickel or copper atoms penetrating into the tungsten phase to form thin solid solution zones, regulating stress distribution and preventing interfacial separation. Upon cooling, supersaturated tungsten precipitates fine phases, pinning grain boundaries and partially restoring the initial structure; however, repeated cycling may accumulate residual changes.

Structural changes are also reflected in defect dynamics. At high temperatures, dislocation climbing is active, vacancy concentration increases, and chemically impurities such as oxygen accumulate at grain boundaries, forming compound films that affect migration rates. Phase distribution changes gradually; the binder phase may expand slightly, but the low expansion coefficient of the tungsten phase buffers overall deformation. The degree of change depends on the duration of environmental exposure; short-term exposure results in better structural recovery, while long-term exposure may lead to recrystallization nuclei, forming new grains and optimizing stability. Chemical bonds are reconstructed during these changes; metallic bonds maintain strength in the tungsten phase, while covalent components enhance heat resistance at the interface. Annealing can control these changes; controlling the cooling rate locks in a favorable structure and avoids excessive coarsening.

Further analysis reveals that the changing temperature threshold is related to the alloy system. The nickel-iron system exhibits progressive coarsening at higher temperatures, while the nickel-copper system responds uniformly due to the thermal conductivity of copper. Impurity control influences the changes; elements such as phosphorus induce localized softening, requiring prior purification. When ambient humidity is present, moisture may promote surface oxidation, causing structural changes to extend from the outside in, forming gradient regions. Mechanical response is correlated with structural changes; under high-temperature creep, particles slide, and the binder phase deforms in a coordinated manner. In thermal

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cycling environments, the changes indicate fatigue accumulation, and grain boundary weakening needs to be mitigated through doping.

4.5.2 Chemical structural resistance of tungsten alloy sheets under radiation environment

Tungsten alloy sheets under radiation environments is primarily based on the response of the material's composite microstructure to energy deposition. This tolerance helps the material maintain the integrity of its chemical bond network and phase structure under the influence of radiation or particles. When bombarded by radiation such as X-rays or electron beams, the high atomic number of the tungsten phase absorbs energy, resulting in cascade displacements. Chemically, atomic bonds briefly break and then reform, forming point defect clusters. The structural tolerance mechanism involves adjustments to the electronic structure; radiation induces electronic excitation, causing outer-shell electrons of tungsten atoms to jump, but these quickly relax and return to equilibrium. The solid solution of the binder phase buffers the impact, and the uniform distribution of nickel or copper atoms disperses energy, preventing localized damage. Interface chemistry plays a role in tolerance; interpenetration of elements in gradient regions enhances bond strength, and radiation-displaced atoms self-heal.

The tolerance is also reflected in defect evolution: radiation generates vacancy-interstitial pairs, chemical diffusion promotes recombination, and reduces accumulation. The phase distribution remains stable; tungsten particles shield the binder phase, reducing radiation flux. The dose dependence of these changes is significant: low doses result in fine-tuning of the structure, while high doses may induce swelling, with slight volume changes that are mitigated by doping. The chemical state responds to radiation; oxide films may form, and surface passivation enhances tolerance. Annealing further aids tolerance; thermal energy drives defect migration, restoring lattice order.

The alloy systems exhibit significant differences in durability. The nickel-iron system shows a coordinated response under magnetic field radiation, while the nickel-copper system distributes energy evenly due to its conductivity. Impurity elements affect durability; oxygen and other elements capture radiation products, forming compounds that require purification and control. Under environmental conditions such as radiative heating, durability shows synergy, with thermal diffusion accelerating defect healing. In mechanical relationships, radiation hardening improves strength, but toughness changes need to be monitored. Under long-term exposure, durability exhibits a gradual change, with the structure adapting to the radiation field and supporting continuous function.

4.5.3 Performance Evolution of Tungsten Alloy Sheets under Extreme Pressure

Tungsten alloy sheets under extreme pressure mainly stems from the compressive response of the structure and the dynamic process of interphase coordination. This dynamic process influences the mechanical behavior and chemical stability of the material, helping to understand the adaptation mechanism under high pressure. When pressure is applied, the lattice of the tungsten phase compresses, the interatomic spacing decreases, the chemical bond strength increases, and the hardness increases. The evolution involves volume changes and overall material shrinkage, but the ductility of the binder phase

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buffers the brittle tendency of the tungsten phase, preventing fragmentation. In this mechanism, dislocation movement is active, the glide system is activated under high pressure, the chemical element distribution is adjusted, and stress concentration is dispersed. The interface plays a crucial role; deformation coordination in the gradient region prevents separation.

Performance evolution is also reflected in the balance between toughness and strength; strength increases initially, toughness gradually decreases, and partial recovery occurs after pressure release. Defect dynamics are exhibited systematically: vacancy compression reduces strength, dislocation walls form, and chemical diffusion promotes stabilization. Phase distribution responds to pressure; tungsten particles are more tightly packed, and the binder phase fills the gaps, optimizing coherence. The pressure threshold for evolution is system-dependent; nickel-iron systems show progressive hardening, while nickel-copper systems respond uniformly due to thermal conductivity. High-pressure treatment after annealing can regulate evolution and restore structural equilibrium.

The regular temperature superposition effect is significant; diffusion is enhanced under high pressure heating, and evolution is accelerated, but this can be controlled by cooling. Impurity elements interfere with the regularity; phosphorus and other elements induce local weak regions, which require purification to alleviate. Environmental factors, such as pressure cycling, cause fatigue in evolution, and gradual structural changes require doping optimization. In terms of chemical properties, bond compression under high pressure improves corrosion resistance and makes the surface barrier denser. Under long-term high pressure, evolution reflects adaptation, and performance tends to stabilize, supporting continuous loads.

4.6 CTIA GROUP LTD Tungsten Alloy Sheet MSDS

CTIA GROUP LTD tungsten alloy sheet MSDS is based on standards such as GB/T 16483-2008 "Contents and Order of Items in Safety Data Sheets for Chemicals". It describes in detail the physicochemical properties, hazard identification and emergency response measures in combination with the specific components of the product, such as the proportion of tungsten, nickel, iron or copper.

Tungsten alloys includes tungsten as the main component, providing the foundation for high density and hardness, supplemented by nickel, iron, or copper as binder phases, with the proportions adjusted according to the series. For example, in the tungsten-nickel-iron system, the nickel-iron ratio balances wetting and strengthening. Trace elements such as carbon and oxygen are controlled at low levels to avoid the formation of embrittlement phases. Chemically, this part uses CAS numbers to identify elements, tungsten CAS 7440-33-7, nickel CAS 7440-02-0. Impurities disclosed include potential contaminants such as phosphorus and sulfur, originating from raw materials, emphasizing purification processes to reduce their content.

The compositional information also includes a description of the alloy phase structure. In the two-phase composite, the tungsten particles are body-centered cubic, and the binder phase is a face-centered cubic solid solution. It is chemically stable with no volatile components. Solubility analysis shows that the material is insoluble in water.

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Chapter 5 Performance Testing and Characterization Methods for Tungsten Alloy Sheets

5.1 Chemical Composition Analysis Techniques for Tungsten Alloy Sheets

Tungsten alloy sheets primarily target their multi-element composite characteristics, employing spectroscopic, fluorescence, and wet chemical methods to achieve qualitative and quantitative detection of major elements such as tungsten, nickel, iron, and copper, as well as trace impurities. These techniques play a role in material quality control, helping to verify alloy proportions, purity, and homogeneity. Atomic absorption spectroscopy and emission spectroscopy are suitable for elemental determination of dissolved samples, X-ray fluorescence spectroscopy provides non-destructive and rapid analysis, and chemical titration is used for specific trace elements. Sample preparation before analysis includes cutting, dissolving, or surface cleaning; dissolution commonly uses a mixture of nitric acid and hydrofluoric acid to treat the refractory tungsten phase. The choice of technique depends on the element type and content; fluorescence methods are suitable for major elements such as tungsten with a high proportion, while highly sensitive spectroscopic methods are required for trace elements. The analytical results guide process adjustments, ensuring the reliability of materials in industrial applications.

These techniques also consider matrix effects; the high density of the tungsten matrix may interfere with the signal, which is mitigated by calibration with standard samples. Non-destructive methods such as fluorescence spectroscopy facilitate online detection, while destructive methods such as absorption spectroscopy offer higher precision. Impurity analysis focuses on oxygen, carbon, phosphorus, etc., which affect tissue stability. Techniques can be combined to form a complete system, such as fluorescence screening followed by precise spectral analysis. Due to environmental factors, analysis must be performed in a clean laboratory to avoid contamination.

5.1.1 Atomic absorption and emission spectral analysis of tungsten alloy sheets

Tungsten alloy sheets are commonly used techniques for elemental quantification after sample dissolution. AAS is based on the absorption of characteristic light by atoms, while AE utilizes the characteristic spectral lines emitted by excited atoms. Combining these two methods can cover major elements such as tungsten, nickel, iron, and copper, as well as trace impurities. In AAS analysis, the sample is dissolved in acid to form a solution, which is then nebulized and introduced into a flame or graphite furnace. Element atoms absorb the characteristic light emitted by a hollow cathode lamp; the absorption intensity is concentration-dependent, and the content is calculated using a standard curve. This method is highly applicable to tungsten alloy sheets, especially when determining low concentrations of nickel or iron, as the chemical ground-state atomic absorption mechanism ensures selectivity. Sample preparation requires attention to the poor solubility of tungsten; a mixture of nitric acid and hydrofluoric acid is commonly used for dissolution. Interference from fluoride ions is avoided by adding boric acid for complexation. Flame AAS is suitable for elements with higher concentrations, while graphite furnace AAS improves the sensitivity for trace element detection.

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Optical emission spectroscopy (OES) introduces dissolved samples into plasma or an electric arc for excitation, detecting characteristic spectral lines emitted by atoms or ions. The intensity is recorded by grating spectroscopy and a detector, enabling simultaneous multi-element determination. In tungsten alloy sheets, tungsten's high melting point requires a high-energy excitation source such as inductively coupled plasma (ICP-OES), where chemically excited state transitions provide rich spectral information. Matrix matching correction is necessary, as the tungsten matrix may cause background interference, which is optimized using internal standard methods or background subtraction. The advantage of OES lies in its rapid multi-element analysis, making it suitable for production batch validation. The two technologies complement each other; AAS is more precise for specific elements, while OES covers a broad spectrum.

The analytical process also involves instrument calibration, establishing curves using certified standard solutions, and ensuring uniform sampling of tungsten alloy sheet samples to avoid segregation. Chemical interferences, such as ionization, are mitigated in OES by adding inhibitors. For safety reasons, acid dissolution requires aeration. Results are typically expressed as mass percentages to help assess the stoichiometric balance of alloy systems such as nickel-iron or nickel-copper.

5.1.2 Quantitative Method for X-ray Fluorescence Spectroscopy Composition of Tungsten Alloy Sheets

X-ray fluorescence spectroscopy (XRF) for quantitative analysis of tungsten alloy sheets is a non-destructive surface analysis technique. It utilizes X-rays to excite sample atoms, producing characteristic fluorescence whose intensity is correlated with elemental content, enabling rapid determination of elements such as tungsten, nickel, iron, and copper. The method is divided into wavelength dispersive (WD-XRF) and energy dispersive (ED-XRF). The former offers high resolution, suitable for precise laboratory analysis, while the latter is portable and suitable for field applications. Sample preparation is simple; the tungsten alloy sheet surface only needs polishing and cleaning to avoid interference from the oxide layer. Chemically, the characteristic X-rays originate from inner-shell electron transitions, ensuring elemental specificity. An excitation source such as an X-ray tube generates primary X-rays, which are absorbed by sample atoms, emitting secondary fluorescence, which is collected by a detector.

Quantitative analysis is based on either the fundamental parameter method or the empirical correction method. The former calculates the matrix effect, while the latter establishes curves using standard samples. The high tungsten content of tungsten alloy sheets causes strong absorption, requiring matrix-matched standards for mitigation. WD-XRF precisely separates spectral lines through crystal spectroscopy, making it suitable for quantifying major elements; ED-XRF, although with lower energy resolution, is highly efficient for simultaneous multi-element detection. The method's advantage lies in its non-destructive nature, preserving sample integrity and facilitating repeatable measurements. Depth analysis is limited to surfaces within a few micrometers and is suitable for uniform sheets.

Chemical interferences, such as overlapping spectral lines, are resolved through software-based spectral analysis. The potential overlap of tungsten L- lines and nickel K-lines requires algorithmic correction.

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Vacuum or helium atmospheres enhance the detection of light elements, but heavy elements are readily available under atmospheric conditions for tungsten alloy sheets. Handheld XRF technology is being extended to rapid screening in production environments. The reliability of the results has been verified using certified reference materials, with deviations controlled within acceptable limits. The system offers high safety, requiring no chemical reagents.

5.1.3 Chemical Titration Analysis of Trace Elements in Tungsten Alloy Sheets

Tungsten alloy sheets is a classic wet chemistry method. It involves dissolving the sample and reacting it with standard reagents; the endpoint is determined by the color change or potential change of an indicator. This method is suitable for specific trace impurities such as phosphorus, sulfur, or certain metal ions. The sample must be completely dissolved before analysis. Tungsten alloy sheets are often treated with a mixture of nitric acid and hydrofluoric acid by heating, which chemically forms a soluble complex of tungsten, avoiding precipitation interference. Trace elements such as phosphorus are often titrated after complexation with phosphomolybdic blue, or sulfur is separated by precipitation before determination. Titration types include redox, complexation, and acid-base titrations, selected based on the properties of the element.

Complexometric titration commonly uses EDTA as the titrant to determine minute deviations in nickel or iron, with chemical equilibrium controlling the reaction. Redox titration is suitable for sulfur or certain transition elements, and potassium permanganate or iodometric titration is commonly used. Indicator selection is crucial; a clear color change indicates the endpoint. Sample volume and concentration must be precise; microanalysis amplifies errors and reduces them through multiple parallel analyses. Chemical separation pretreatment is necessary; for example, phosphorus must be extracted from the tungsten matrix to avoid interference from the main element.

The method's advantages lie in its simple equipment, low cost, and suitability for laboratory verification of spectral results. Sensitivity can be improved through reaction amplification, such as spectrophotometric endpoint determination. Safety precautions include ensuring proper ventilation during acid handling and avoiding the hazards of hydrogen fluoride.

5.2 Microstructure Characterization Methods for Tungsten Alloy Sheets

Tungsten alloy sheets primarily utilizes electron microscopy (SEM), spectral analysis, and diffraction techniques. These methods reveal the grain distribution, phase composition, and defect characteristics of the material at different scales, aiding in understanding the relationship between structure and properties. Scanning electron microscopy (SEM) is used for surface morphology and compositional distribution, X-ray diffraction (XRD) analyzes phases and crystal structures, and transmission electron microscopy (TEM) focuses on internal defects. Sample preparation before characterization involves cutting, polishing, and ion thinning to ensure no contamination. The choice of method depends on the research focus: SEM is preferred for surface analysis, diffraction for crystal information, and TEM for nanoscale defects. Combining these methods creates multi-dimensional characterization; for example, combining

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SEM and diffraction can confirm phase structure. The chemical basis of these methods lies in the interaction between electrons and matter, with excitation signals reflecting atomic arrangement. Environmental control, such as vacuum, is crucial to prevent oxidation.

5.2.1 Scanning electron microscopy morphology and composition mapping of tungsten alloy sheets

Tungsten alloy sheets is a common method for characterizing microstructure. By scanning the sample surface with an electron beam to generate secondary and backscattered electron signals, the morphology of tungsten particles, the distribution of the binder phase, and interface characteristics are revealed. Simultaneously, energy-dispersive spectroscopy (EDS) maps the spatial distribution of elements. This method is based on the interaction between electrons and atoms. Incident electrons excite sample atoms to generate characteristic signals, secondary electrons reflect surface morphology, and backscattered electrons depend on differences in atomic number. Tungsten's high atomic number makes its particles brighter than the binder phase, facilitating differentiation. Sample preparation includes mechanical polishing followed by electrolytic or ion polishing. The surface needs to be conductively plated with carbon or gold to avoid charging effects. Imaging is performed in a vacuum environment, with acceleration voltage adjustments to balance resolution and penetration depth; low voltage is suitable for surface details, while high voltage allows for deeper observation.

In morphological observation, the two-phase structure of the tungsten alloy sheet is clearly revealed. Tungsten particles are spherical or polyhedral, with the binder phase filling the gaps to form a continuous network. The magnification can be adjusted to examine grain boundary cracks or pores. Chemical composition mapping utilizes an X-ray detector to collect characteristic peaks, and software processing generates elemental distribution maps. Tungsten regions show dense signals, while nickel or iron is enriched in the binder phase, revealing segregation or gradient regions. Mapping resolution depends on detector efficiency and scan time; longer scans improve the signal-to-noise ratio. The advantage of this method lies in its intuitive combination of morphological and chemical information, aiding in the analysis of structural defects caused by sintering inhomogeneity. Auxiliary modes such as electron backscatter diffraction can further characterize crystal orientation; chemically, elements segregating at grain boundaries affect the diffraction pattern.

Furthermore, this method plays a role in tracking structural changes after heat treatment; comparisons of annealed samples show improved particle spheroidization and interphase bonding. Environmental scanning modes allow for wet sample observation, but tungsten alloy sheets are typically analyzed in a dry state. Image processing software assists in quantifying particle size distribution and phase volume fraction; chemical mapping data can be overlaid with morphology images to provide a composite view. Mapping of impurity elements such as oxygen reveals the location of oxide inclusions, guiding purification processes. The limitation of this method lies in its surface sensitivity; cross-sectional observation is required to assess deep structure. In summary, scanning electron microscopy morphology and composition mapping provide a comprehensive microscopic characterization approach for tungsten alloy sheets, enabling visualization of structural chemistry through electronic signal mechanisms and

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supporting quality assessment of materials in precision applications. This method also allows for the effective identification of structural heterogeneity, driving the optimization of processing parameters.

5.2.2 X-ray diffraction phase and crystal structure analysis of tungsten alloy sheets

Tungsten alloy sheets is a non-destructive characterization technique. It utilizes the interaction of X-rays with the atomic planes of a crystal to generate diffraction peaks, identifying phase composition and resolving lattice parameters to aid in understanding the phase equilibrium and structural stability of the alloy system. This analysis is based on Bragg's law: incident X-rays are reflected by the crystal, peak positions correspond to interplanar spacing, and intensity reflects atomic arrangement. Samples can be whole sheets or powders, with smooth surfaces to avoid scattering interference. Cu-K α rays are commonly used as the source, detectors collect diffraction signals, and software matches standard cards to identify phases, such as the body-centered cubic peaks of tungsten and the face-centered cubic peaks of the binder phase. In phase analysis, tungsten alloy sheets show strong and sharp tungsten peaks, while the binder phase peaks are weaker. The dissolution of alloying elements causes peak shifts, revealing the degree of solid solution .

Crystal structure analysis involves peak fitting to calculate lattice constants. The α -parameter of the tungsten phase changes only slightly with temperature, while the binder phase expands or contracts depending on the iron or copper ratio . The influence of chemical composition on diffraction is reflected in peak width; grain refinement leads to broadening, while recrystallized samples show peak narrowing . Quantitative phase analysis estimates volume fractions using integrated intensity ratios, aiding in understanding sintered phase formation. The advantages of this method include rapid scanning of batches of samples, operable in both laboratory and portable devices. Advanced modes, such as in-situ heating diffraction, track high-temperature phase transitions and chemically observe tungsten dissolution behavior. Data processing includes background subtraction and peak separation ; complex spectra require multi-peak fitting.

Furthermore, this analysis is effective in evaluating rolled deformation structures; variations in texture peak intensity reflect orientation distribution, and chemically, deformation-induced strain affects peak shift. Impurity phases, such as oxides, have weak but detectable peaks , guiding purification. Environmental control using vacuum or inert gas avoids interference from oxidation peaks. The diffraction results are confirmed by combining these methods with other characterization techniques, such as electron microscopy.

5.2.3 Observation of microscopic defects in tungsten alloy sheets using transmission electron microscopy

Tungsten alloy sheets is a high-resolution characterization technique. By using a high-energy electron beam to penetrate thin samples and generate bright-field and dark-field images and diffraction patterns, it reveals nanoscale defects such as dislocations, vacancies, grain boundaries, and precipitates, aiding in the analysis of the impact of structure on performance. This observation is based on the interaction

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between electron waves and the crystal; transmission electron microscopy reveals defect contrasts, while electron diffraction provides local crystal information. Samples need to be ionically thinned to tens of nanometers to avoid bending or contamination. High accelerating voltages are used to penetrate the high density of tungsten. Chemically, electron scattering depends on atomic number, and tungsten has a relatively strong contrast with the binder phase. In defect observation, dislocation lines appear bent in the bright-field image, and the segregation of chemical dislocation core elements affects migration.

Grain boundary observation reveals interface structure; high-resolution imaging shows atomic arrangement; chemically, segregating elements such as boron accumulate at the interface, enhancing bonding. Precipitated phases, such as fine tungsten particles, are imaged in a lattice within the binder phase, allowing observation of their shape and distribution. Dark-field imaging highlights specific defects, and diffraction comparisons analyze dislocation types. The advantage of this method lies in its atomic-level resolution, combined with energy filtering to eliminate thickness effects. In-situ heating is used to observe defect dynamics, chemically healing vacancies through high-temperature diffusion. Data processing includes image filtering and simulation matching to confirm the defect model.

Furthermore, this observation is effective in tracking rolling deformation defects; cold-worked samples show high-density dislocation networks that decrease after annealing. Impurity-induced defects, such as needle-like compounds, can be imaged to guide control. A high ambient vacuum is used to avoid carbon contamination. The method combines scanning transmission mode (STEM) elemental mapping to expand the chemical information of defects.

5.3 Performance Indicators Testing Specifications for Tungsten Alloy Sheets

Tungsten alloy sheets are primarily based on national standards, industry standards, and internal company specifications. These specifications cover methods for determining key parameters such as density, hardness, mechanical strength, thermal conductivity, and electrical conductivity, ensuring the consistency and reliability of the material in industrial applications. The testing process emphasizes sample representativeness, instrument calibration, and environmental control, such as operation under constant humidity and room temperature conditions. Density and packing density are measured using the water displacement method or gas displacement method, while hardness is determined using Brinell, Vickers, or Rockwell methods. The specifications also include repeatability requirements, with average values from multiple samples to reflect uniformity. Chemical composition affects performance testing; measurement error correction must be considered when tungsten content is high. Test reports must record the instrument model, standard number, and deviation analysis.

5.3.1 Methods for testing the density and packing density of tungsten alloy sheets

Tungsten alloy sheets are the Archimedes' water displacement method and the gas displacement method. The former is suitable for routine laboratories, while the latter is suitable for high-precision samples or samples that are not suitable for immersion in liquid. This method calculates the material density based on the principle of volume displacement and evaluates the packing density by comparing it with the

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theoretical density. In the water displacement method, the sample is first dried and weighed, then immersed in distilled water or ethanol and weighed for wet weight. Chemically, the liquid should be chosen to avoid reacting with the alloy and prevent surface dissolution. The calculation formula takes into account liquid density and temperature correction to ensure accurate measurement. When the sample shape is regular, the volume is measured directly; for irregular sheets, they are suspended and immersed with a thin thread. Multiple measurements are taken and averaged to reduce interference from air bubbles.

The gas displacement method uses helium or nitrogen. The sample is placed in a container of known volume, and changes in gas pressure reflect the sample volume. Chemically inert gases prevent oxidation. The method's advantage lies in its dry-state operation, making it suitable for thin sheets or easily oxidized surfaces. Density calculations require a theoretical density reference, based on a weighted average of components; when tungsten is dominant, the theoretical value is close to that of pure tungsten. Testing specifications require clean samples, free of oil or oxide scale, and measurements taken after surface polishing. The ambient temperature is controlled at standard room temperature, and humidity is low to prevent the influence of adsorbed water.

Furthermore, this method is widely used in production batch verification, with multi-point sampling to assess uniformity and tracing the sintering process when deviations are large. Chemical purity affects the results; impurities and porosity reduce the measured density. Standard blocks are used for instrument calibration and periodic verification is necessary. When testing thin sections, stacking or folding is required to avoid bending errors. Results are expressed in grams per cubic centimeter as a percentage of density. Specifications emphasize safety; for the water displacement method, attention should be paid to liquid evaporation, and for the gas method, sealing should be checked.

5.3.2 Test method for hardness of tungsten alloy sheets

Tungsten alloy sheets include Brinell hardness, Vickers hardness, and Rockwell hardness tests. The choice depends on the material thickness and the expected value. Brinell hardness is suitable for overall hardness, while the latter two are used for surface or thin sheets. These methods assess resistance to plastic deformation based on the size or depth of the indentation. Brinell hardness testing uses a steel ball or cemented carbide ball indenter, which is pressed into the sample surface under a specified load. After holding for a specified time, the indentation diameter is measured to calculate the hardness value. Chemically, the indenter material must be wear-resistant to avoid scratching by the tungsten phase. The sample surface should be polished smooth and of sufficient thickness to prevent deformation on the back side. The load selection considers the high hardness of the alloy and is typically high to produce a clear indentation.

Vickers hardness testing uses a diamond pyramid indenter with a wide load range, suitable for micro-area measurements. Indentation diagonal measurements are taken under a microscope, and the chemical inertness of diamond ensures accuracy. Low loads are used for thin sheet testing to avoid penetration. Rockwell hardness testing is rapid, with preload followed by main load; depth difference readings are taken directly, and HRA or HRC scales are suitable for tungsten alloy sheets. Specifications require

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multi-point testing, grid distribution averaging, and evaluation of uniformity. Environmental vibration control and horizontal instrument placement are essential.

Furthermore, this method is effective in post-heat treatment performance tracking, showing a recovery from the decrease in hardness observed in annealed samples. Chemical composition affects the results; a higher proportion of the binder phase results in lower hardness. Surface treatments such as coatings must be removed from the substrate before measurement. Standard blocks are used for instrument calibration and periodic verification. Thin sheet bending and fixing tests are performed to avoid edge effects. Results are expressed in HB, HV, or HR units, with the load specified. Specifications emphasize safety; indenter protection is used to prevent breakage.

5.3.3 Test methods for corrosion resistance of tungsten alloy sheets

The corrosion resistance of tungsten alloy sheets include immersion tests, electrochemical tests, and salt spray tests. These methods simulate different corrosive environments to assess the material's resistance to acidic, alkaline, and saline media, helping to optimize surface protection and composition design. Immersion tests are the most basic method. Samples are placed in a specified corrosive medium, and weight changes, surface morphology, and solution composition are observed periodically. Chemically, media such as sulfuric acid, hydrochloric acid, or sodium chloride solutions are selected, and temperature and time are set according to standards. After the test, the sample is cleaned, the weight loss is measured to calculate the corrosion rate, and surface metallographic observation records pitting or uniform corrosion characteristics. The advantage of this method is its simplicity and intuitiveness, making it suitable for long-term corrosion behavior studies.

Electrochemical testing provides dynamic corrosion information, primarily using polarization curves and impedance spectroscopy analysis. The sample serves as the working electrode, immersed in an electrolyte within a three-electrode system. Potential scanning records current changes, and the corrosion current density is calculated using the Tafel extrapolation method. The self-corrosion potential reflects thermodynamic stability. AC impedance spectroscopy measures interfacial resistance and capacitance, and an equivalent circuit model is fitted to evaluate the passivation film's protective effect. Due to the high reactivity of the binder phase in tungsten alloy sheets, the stability of the reference electrode must be carefully considered during testing. Salt spray testing simulates a marine environment, with sodium chloride solution sprayed into a neutral salt spray chamber. Surface rust or pitting is periodically observed; chemically, chloride ion penetration induces localized corrosion, and the rating criteria are based on the corrosion area.

Testing specifications require samples to have a consistent surface condition; testing after polishing or coating must be noted. Environmental control should ensure constant temperature and humidity, avoiding external interference. Multiple parallel tests should be conducted, and the average value should be used to statistically analyze corrosion depth or rate. Corrosion products should be chemically analyzed, and oxide phases should be identified using X-ray diffraction. A combination of methods should be used,

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including qualitative immersion, quantitative electrochemical analysis, and accelerated salt spray testing. Safety precautions include ensuring proper ventilation of acid mist and neutralization of waste liquid.

5.3.4 Test method for wear resistance of tungsten alloy sheets

The main methods for testing the wear resistance of tungsten alloy sheets include pin-disc wear tests, grinding wheel wear tests, and reciprocating friction tests. These methods simulate wear behavior under dry friction or lubrication conditions, assess the volume loss and coefficient of friction of the material under contact stress, and help optimize hardness and surface treatment. In the pin-disc wear test, the sample is fixed as a disc, and a load is applied to the pin for rotation. Chemical frictional heat induces oxidative wear, and the wear rate is calculated by recording the weight loss or wear track depth. The load and rotation speed are adjustable to simulate different working conditions. Dry friction highlights adhesive wear, while lubrication examines the effect of abrasive particles.

The grinding wheel wear test uses a standard grinding wheel to grind the sample surface, measuring the weight loss per unit time. Chemically, abrasive grain embedding induces cutting wear, suitable for high-hardness tungsten alloy sheets. Test specifications control the grinding wheel grit size and pressure to ensure repeatability. The reciprocating friction test simulates linear motion, with a ball or pin sliding back and forth on the sample. Sensors record the frictional force in real time, calculating the average coefficient. Chemically, surface fatigue leads to spalling, and the wear track microstructure is observed to analyze the mechanism. Laser confocal microscopy or profilometry quantifies the wear track volume.

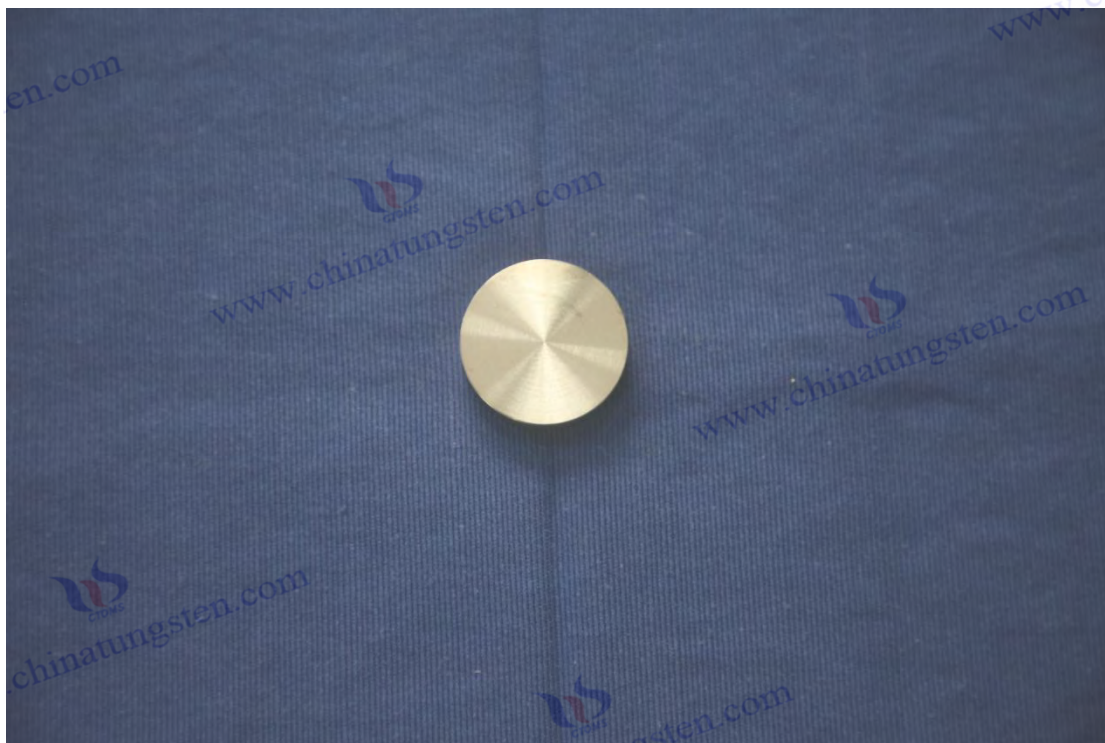
The testing specifications require uniform sample surface polishing and multi-directional testing to assess anisotropy. The environment must be controllable, considering factors such as humidity's influence on oxidative wear. Chemical cleaning removes wear debris, ensuring high weighing accuracy. Scanning electron microscopy is used to analyze the worn surface, and energy dispersive spectroscopy identifies the transfer film. A combination of methods is employed, including pin-disc quantification of volume loss and reciprocating dynamic coefficients. Safety precautions include dust collection to prevent inhalation.

5.3.5 Test method for the strength of tungsten alloy sheets

Tungsten alloy sheets include tensile testing, bending testing, and compression testing. These methods measure the tensile strength, yield strength, and fracture behavior of the material, helping to assess its mechanical reliability and processing adaptability. Tensile testing is the most commonly used method. Samples are machined into standard dumbbell or rectangular strips and subjected to uniaxial tension on a universal testing machine. The load-displacement curve is recorded, and chemical dislocation slip dominates plastic deformation. Tensile strength and elongation are calculated. Non-contact extensometers are used for sheet testing to avoid clamping damage. The strain rate is controlled slowly to capture quasi-static behavior.

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Bending tests are suitable for thin sheets, applying three- or four-point bending loads to measure bending strength and deflection. Chemical analysis assesses surface compression and inner layer tensile compatibility, evaluating interlayer bonding. Compression tests are for thick sheets or blocks, with axial compression of short cylindrical samples recording stress-strain. Tungsten alloy sheets exhibit limited plasticity at high densities. Test specifications require standardized sample dimensions and a defect-free surface. The ambient temperature is adjustable to examine high-temperature strength decay. Crack propagation is monitored in real-time during testing, aided by acoustic emission. Chemical analysis of the fracture surface and scanning electron microscopy observation of dimples or cleavage features differentiate fracture modes.



CTIA GROUP LTD Tungsten Alloy Sheets

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Chapter Six: Preparation Process of Tungsten Alloy Sheets

6.1 Tungsten Alloy Sheet Preparation Process and Classification

Tungsten alloy sheets mainly revolve around the basic route of powder metallurgy. This process involves multiple unit operations from raw material powder to finished sheet, including powder mixing, pressing, sintering, thermomechanical processing, and post-treatment. Classification is based on alloy system, target properties, and thickness specifications. The main preparation route is centered on liquid-phase sintering, supplemented by solid-phase or activated sintering variants. The process design considers the refractory and high-density characteristics of tungsten to ensure densification and uniform microstructure. A typical process begins with the uniform mixing of high-purity tungsten powder and binder powder, followed by cold isostatic pressing to form a billet, high-temperature sintering to achieve particle rearrangement and bonding, and then gradual thinning through hot rolling, warm rolling, and cold rolling, with intermediate annealing to release stress, and finally surface finishing. In terms of classification, high-density sheets emphasize tungsten content and density, while non-high-density sheets may introduce pseudo-alloys or composite structures. Thickness range affects process selection; thin sheets require precision rolling, while thick sheets focus on initial blanking.

The flexibility of the preparation process allows for adjustments based on the application; for example, medical shielding sheets emphasize uniformity, while industrial wear-resistant sheets emphasize hard phase reinforcement. Chemical principles permeate the entire process: liquid phase wetting drives densification during sintering, and deformation coordination during processing relies on the plasticity of the binder phase. Environmental control, such as using a hydrogen atmosphere to prevent oxidation, and purity management to avoid introducing defects through impurities, are crucial. Process optimization, particularly the integration of hot isostatic pressing and spark plasma sintering in recent years, improves the quality of initial blanks and reduces the difficulty of subsequent processing. Classification can also be based on the sintering method: traditional hydrogen furnace sintering and vacuum sintering. The former is lower in cost, while the latter offers superior impurity control.

6.1.1 Main preparation route of tungsten alloy sheets

Tungsten alloy sheets are based on powder metallurgy, and can be divided into three types: traditional liquid phase sintering, activated sintering, and melt infiltration composite routes. These routes are selected according to the alloy system and performance objectives to ensure a complete transformation from powder to sheet. The traditional liquid phase sintering route is the most mature approach. First, tungsten powder is mechanically mixed or ball-milled with nickel, iron, or copper powder in a specific ratio. The mixture is then cold isostatically pressed into a large-sized billet. Subsequently, under hydrogen protection, the temperature is raised above the liquid phase emergence temperature and held to promote the melting and wetting of the binder phase and the densification of tungsten particles, achieving rearrangement and dissolution-re-precipitation. After sintering, the billet is forged at high temperature or hot-rolled to gradually reduce its thickness to an intermediate level, and then subjected to warm rolling

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and cold rolling, accompanied by multiple vacuum annealing processes to relieve stress. Finally, it is pickled or polished into sheets.

The activated sintering route is designed for systems that are difficult to densify. A small amount of activators such as palladium and nickel are pre-added to the powder to lower the sintering temperature and promote solid-phase diffusion. Chemically, the activators agglomerate at the interface, reducing surface energy. This route is suitable for tungsten-copper or high-tungsten-content sheets. Its advantages include low energy consumption and refined microstructure, but activator residue requires subsequent treatment. The melt-infiltration composite route first presses and sinters a porous tungsten framework, then vacuum-infiltrates copper or silver liquid. Chemically, the liquid metal fills the pores, forming a pseudo-alloy structure. Subsequent rolling facilitates ultra-thinning, making it suitable for thermally and electrically conductive sheets.

The selection of the production route takes into account scalability and cost. Traditional routes are suitable for mass production of nickel-iron and nickel-copper systems, while melt infiltration routes are designed for tungsten-copper series. Auxiliary processes such as hot isostatic pressing can be incorporated into any route to improve initial density and reduce rolling cracks. Chemical control is implemented throughout the route, atmosphere dew point management prevents oxidation, and powder particle size matching affects mixing uniformity. Surface treatments such as chemical plating are integrated into the route ends to improve corrosion resistance. Due to environmental factors, recycled scrap materials are pulverized and reused.

6.1.2 Process differences between high-density tungsten alloy sheets and non-high-density sheets

High-density tungsten alloy sheets and non-high-density sheets lie in composition design, sintering parameters, and processing paths. The former aims to maximize tungsten content and density, while the latter focuses on specific functions such as thermal conductivity or low-density equilibrium. High-density sheets typically have a higher tungsten content and a lower proportion of binder phase. The process employs extended liquid phase holding and secondary hot isostatic pressing to minimize porosity and chemically reduce the volume of the soft phase to approximate the theoretical density. Sintering temperature is precisely controlled within the appropriate liquid phase range to avoid excessive flow leading to collapse. The processing path emphasizes high-reduction hot rolling followed by rigorous intermediate annealing to maintain uniform microstructure and high thickness uniformity in the finished product.

For non-high-density sheet materials, such as tungsten-copper pseudo-alloys, the tungsten content can be reduced, and the process shifts to melt infiltration. First, the tungsten framework is sintered, leaving intentional porosity, and then copper is infiltrated to fill the voids. Chemically, the copper phase does not form a solid solution, providing a high thermal conductivity channel. The sintering temperature is lower, and the processing path focuses more on cold rolling adaptability. Due to copper's good plasticity, it is easy to achieve ultra-thinness without frequent annealing. Activated sintering variants are common in non-high-density sheets, with additives promoting low-temperature densification, suitable for tungsten-

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silver or composite systems. Differences also lie in surface treatment; high-density sheets are often nickel-plated to protect the binder phase, while non-high-density sheets directly utilize copper's corrosion resistance.

Furthermore, process differences affect energy consumption and yield. High-density processes require sophisticated equipment and have long lead times, but offer stable performance; non-high-density processes are more flexible and suitable for small-batch functional wafer production. Chemical purity management is stricter in high-density processes, as impurities can easily amplify porosity. In terms of environmental control, high-density processes require high-purity hydrogen, while non-high-density processes use vacuum melting infiltration to prevent oxidation.

6.1.3 Typical thickness range and corresponding process selection (0.05 mm to 50 mm)

Tungsten alloy sheets typically range in thickness from 0.05 mm ultrathin foil to 50 mm thick plates. The corresponding process selection requires a balance between processing difficulty and microstructure control. Thin sheets emphasize precision rolling, while thick sheets focus on billet preparation and forging. For the 0.05 mm to 0.5 mm ultrathin range, multi-pass cold rolling is the primary process, resulting in a high overall processing yield. A slight increase in the proportion of the binder phase is used to improve ductility and prevent edge cracks. Intermediate annealing is frequently performed under high vacuum to release stress, and lubricants are used to reduce surface damage. Finally, chemical polishing or electrolytic finishing ensures a smooth surface.

The process is most mature for plates with a thickness of 0.5 mm to 10 mm, from hot rolling to cold rolling finishing. Hot rolling involves large reductions in each pass, with warm rolling transitions and optimized annealing processes that result in fibrous microstructure. For plates with a thickness of 10 mm to 50 mm, the process focuses on initial forming, followed by hot forging or hot rolling to thin large-size cold isostatically pressed billets. A high-temperature protective atmosphere is used to prevent decarburization, and the machining rate is lower to retain strength. The surface is mostly removed by milling to remove the oxide layer.

Process selection considers equipment capabilities: thin sheets require high-precision rolling mills and tension control, while thick sheets require large forging presses. Chemical principles are reflected in the thickness: thin sheets dissipate heat quickly and exhibit significant work hardening; thick sheets experience accumulated thermal effects, necessitating temperature gradient control. Uniformity management becomes increasingly difficult with thickness, requiring multi-point density testing for thick sheets. Environmental factors also play a role; thin sheets are prone to oxidation and require inert gas packaging.

6.2 Preparation of raw material powder

Raw material powder preparation is a fundamental step in tungsten alloy sheet production, directly affecting the uniformity, density, and final properties of the sintered structure. This preparation involves

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The reduction and purification of tungsten powder, the selection and pretreatment of alloying element powders, and homogenization through mixing. Tungsten powder, as the main raw material, requires high purity and suitable particle size to ensure wetting and rearrangement during liquid-phase sintering. Alloying element powders such as nickel, iron, and copper provide a binder phase and must match the particle size and activity of the tungsten powder. The preparation process emphasizes the control of chemical purity and physical properties to avoid introducing impurities into brittle phases or pores. A typical process begins with the hydrogen reduction of ammonium tungstate, progressing to alloy powder atomization or carbonyl decomposition, followed by sieving and mixing to achieve uniform batching. Particle size distribution and Fisher's sieve method detection are key quality control points to ensure powder flowability and pressing performance.

The chemical principle behind the preparation lies in reduction reactions and surface energy regulation. High-purity hydrogen is used to reduce and remove oxygen, and the alloy powder is pretreated to prevent oxidation. Modern processes incorporate spray drying or mechanical alloying to improve mixing efficiency and refine the microstructure. Due to environmental factors, the powder must be stored in a dry, inert atmosphere to prevent moisture absorption. The quality of the raw materials directly affects the uniformity of the finished product's thickness and the defect rate; fine powder is beneficial for thin sheet production, while coarse powder is suitable for thick plates.

6.2.1 Preparation and Quality Requirements of High-Purity Tungsten Powder

The preparation of high-purity tungsten powder mainly employs the hydrogen reduction route of ammonium tungstate or tungsten oxide. This route achieves high purification and particle size control of tungsten through multi-stage reduction, ensuring the activity and cleanliness of the powder during alloy sheet sintering. The preparation process begins with the dissolution and recrystallization purification of ammonium tungstate, followed by calcination to produce yellow tungsten or blue tungsten oxide. Subsequently, it undergoes staged hydrogen reduction in a tube furnace or pushboat furnace. The first stage involves low-temperature reduction to remove water of crystallization and some oxygen, while the second stage involves high-temperature reduction to produce metallic tungsten powder. Chemically, the reduction reaction involves WO_3 reacting with H_2 to produce W and H_2O . Water vapor is promptly removed through dew point control to prevent re-oxidation of the tungsten powder. Process parameters such as boat speed, hydrogen flow rate, and temperature gradient regulate powder particle size; lower temperatures and slower speeds favor the formation of finer powder.

Quality requirements focus on purity, particle size, and morphology. Purity requires low oxygen content and trace amounts of alkali metals and phosphorus/sulfur to prevent sintering defects. Particle size is typically determined using the Fisher method; fine powder promotes densification, while coarse powder provides strength. Morphology requires near-spherical or polyhedral shapes with clean, agglomerated surfaces to facilitate mixing and flow. Testing includes chemical analysis of impurities, scanning electron microscopy observation of morphology, and laser particle size distribution analysis. During preparation, the raw material ammonium tungstate undergoes multiple recrystallizations to remove sodium and

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calcium, and is dried with high-purity hydrogen. Variant processes such as plasma reduction or zinc fusion are used to recover tungsten, further improving purity.

The quality requirements for this preparation are related to the application of the alloy sheet. Medical shielding sheets require extremely low impurities to avoid radiation scattering, while industrial wear-resistant sheets allow for slightly coarser grains to enhance hardness. Storage requires vacuum or inert gas packaging to prevent moisture and oxidation. Chemical stability is a core requirement; the powder is prone to passivation in air, forming a thin oxide layer that affects wetting, necessitating pre-reduction activation.

6.2.2 Selection and Pretreatment of Alloy Element Powders (Ni, Fe, Cu, Co, Mo, etc.)

Alloying element powders such as nickel, iron, copper, cobalt, and molybdenum are crucial for tungsten alloy sheet formulation. Element selection is based on phase diagram wettability and functional matching, while pretreatment ensures powder activity and purity, preventing uneven sintering. Nickel powder is commonly prepared using carbonyl decomposition, resulting in fine particle size, high activity, and good ductility; iron powder is prepared by electrolysis or reduction, offering moderate magnetic properties to aid mixing; copper powder is prepared by atomization or electrolysis, providing excellent thermal conductivity for non-magnetic systems; cobalt powder strengthens the binder phase; and molybdenum powder partially replaces tungsten to regulate expansion. Selection criteria include high purity, low oxygen content, and particle size matching with tungsten powder, typically with similar Fisher particle sizes to prevent segregation.

Pretreatment includes hydrogen reduction to remove the surface oxide layer; chemically, H₂ reacts with the oxides to generate water, which is then discharged, increasing the wetting angle. Vacuum degassing further reduces gaseous impurities, and sieving removes agglomerates and foreign matter. Ball milling or mechanical activation pre-alloys certain elements, such as premixed nickel-iron, to form a solid solution powder, improving uniformity. The processing temperature is controlled gently to avoid powder sintering. Chemical cleaning, such as acid washing, removes oil stains, but tungsten alloy powders are often treated with dry methods for corrosion prevention.

Furthermore, the differences in selection and pretreatment reflect the system requirements: iron powder in the nickel-iron system needs rust prevention, while copper powder in the nickel-copper system has strong oxidation resistance. High-purity molybdenum powder is selected for atomization to match the density of tungsten. Quality testing includes chemical analysis of oxygen, carbon, and particle size distribution.

6.2.3 Powder Particle Size Distribution Control and Fisher Particle Size Detection

The core quality control methods in the preparation of tungsten alloy sheet raw materials. Distribution optimization is achieved by adjusting reduction parameters and sieving, while the Fisher method provides an average particle size assessment to ensure pressing and sintering performance. Particle size

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distribution control is reflected in the reduction of tungsten powder; high temperatures and fast boat speeds produce coarse powder, while low temperatures and slow speeds produce fine powder. Chemically, reduction kinetics affect crystal nucleus growth, and adjusting hydrogen flow rate and water vapor concentration suppresses abnormal coarsening. Alloy powder atomization or grinding controls the narrowing of the distribution, avoiding agglomeration caused by extremely fine powder or porosity caused by coarse powder. Laser particle size analyzers or sieving methods monitor the distribution curve; ideally, it should be log-normal, with a wide distribution facilitating narrowing and densification.

Fisher particle size distribution is based on the principle of air permeation. Powder layer resistance reflects the average particle size, and chemical surface adsorption of gases affects permeation, but repeatability is good under standard conditions. The test sample is dried and uniformly packed, and the sub-sieve diameter is calculated based on the pressure difference. The method is simple and rapid, suitable for production control, and covers a typical range of tungsten powder from fine to coarse to match thickness requirements. Control is combined with mixing adjustments; fine tungsten powder is mixed with coarse alloy powder to optimize flow.

This control and detection is related to the uniformity of the finished product; a narrow distribution is beneficial for defect-free thin sheets, while a wide distribution results in thick sheets with high strength. Chemical purity affects the detection; high oxygen levels and powder agglomeration lead to larger readings. Environmental humidity control is crucial to prevent the sample from absorbing water.

6.2.4 Powder Mixing and Alloying Methods

Powder mixing and alloying are homogenization steps in tungsten alloy sheet preparation. Uniform element distribution is achieved through mechanical mixing, ball milling, or spray drying to avoid sintering segregation. Mechanical mixing commonly uses V-type or double-cone mixers with low-speed rotation to prevent separation. Chemically, electrostatic or van der Waals forces on the powder surface affect uniformity, and additives such as alcohol assist dispersion. The mixing time can be extended to several hours to ensure random mixing. Ball milling alloying utilizes high-energy ball milling, where impact induces mechanochemical reactions, pre-alloying some elements, refining particle size, and improving activity. However, inert gas protection is required to prevent oxidation.

Spray drying atomizes and dries a powder suspension into spherical particles, temporarily binding them with a chemical binder to improve flowability and compressibility. The method's advantage lies in the uniformity of the composite powder, making it suitable for large-scale production. After mixing, samples are taken for chemical analysis or electron microscopy to verify the distribution; uniformity is defined by low elemental deviation.

The differences in these methods reflect production scale: mechanical mixing is simple and low-cost, ball milling is suitable for refining microstructures, and spray drying achieves high-quality uniformity. The chemical principles involve diffusion and adsorption, and mixing promotes surface contact. Storage is crucial to prevent separation, and vibration should be avoided.

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6.3 Powder Molding Process

Powder molding is a crucial step in tungsten alloy sheet production, connecting raw powder with sintered blanks. It transforms loose powder into green blanks with a specific shape, strength, and density by applying pressure or using auxiliary media. This process directly impacts the uniformity of shrinkage during subsequent sintering and the consistency of the finished product's microstructure. Molding methods include cold isostatic pressing, compression molding, and injection molding, chosen based on powder characteristics, blank size, and thickness targets. Tungsten alloy powders have poor flowability and compressibility, requiring consideration of tungsten's high density and the wetting effect of the binder phase during molding. The process principles involve particle rearrangement, plastic deformation, and friction effects; the uniformity of pressure distribution determines the green blank density gradient. Sufficient green blank strength is necessary to support handling and debinding, preventing cracking or deformation. Chemical additives such as paraffin or polymers temporarily reinforce the bond and are subsequently removed.

In recent years, the optimization of molding processes has focused on greening and automation. Cold isostatic pressing is suitable for large-sized blanks, compression molding is suitable for small and medium-sized parts, and injection molding has been extended to complex-shaped thin blanks. Environmental control, such as a dry atmosphere to prevent powder oxidation and slow pressure release to avoid springback, is crucial. The density of the green blank after molding is usually a certain percentage of the theoretical value, and optimization can reduce differences in sintering shrinkage. Defect control focuses on delamination and density inhomogeneity, which are mitigated by adjusting process parameters.

6.3.1 Cold Isostatic Pressing

Cold isostatic pressing (COP) is a method for preparing tungsten alloy sheet blanks. It uses a liquid medium to transmit uniform pressure, compressing powder into a flexible mold to form a high-density green blank. This method is suitable for large-sized or complex-shaped blanks, ensuring isotropic pressure. The process involves filling a rubber or plastic mold with mixed powder, sealing it, and then placing it in a high-pressure container. Water or oil is used as the pressure-transmitting medium, and the pressure is gradually increased to the desired level. After maintaining this pressure for a period, the blank is depressurized and removed. Chemically, uniform pressure promotes compact rearrangement of particles, reducing density gradients caused by friction. The high hardness of tungsten powder effectively fills gaps under isostatic pressing, and the binder phase powder assists in coordinated deformation.

The advantages of this molding process lie in the uniform density distribution of the green blank, making it suitable for subsequent sheet rolling and avoiding the low-density areas at the edges commonly found in molding. The flexible die design allows for the production of cylindrical, plate-shaped, or irregularly shaped blanks, and the addition of a small amount of lubricant improves filling flow. Slow pressure release control prevents micro-cracks caused by elastic rebound. Green blank strength is enhanced through powder particle size matching; finer powders offer good filling properties but require protection

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against agglomeration. Optimization of process parameters involves the pressurization rate and holding time; longer holding times promote particle locking.

This forming process is widely used in the production of high-density tungsten alloy sheets. Large billets, after cold isostatic pressing, undergo high efficiency in hot rolling. Chemical purity management is crucial; a clean medium is essential to avoid contamination. The green billet surface is smooth after demolding, reducing subsequent machining allowances. Variations such as the dry-bag method simplify operations, while the wet-bag method offers greater flexibility. Due to environmental factors, recycling mold materials reduces costs.

6.3.2 Compression Molding and Pressure Parameter Optimization

Compression molding and pressure parameter optimization are traditional methods for producing small-sized blanks of tungsten alloy sheets. This method involves compressing powder into shape using unidirectional or bidirectional pressure applied through a steel mold. The equipment is simple, making it suitable for mass production. Optimization focuses on pressure distribution and smooth demolding. The process involves filling a hard mold with powder, applying pressure with a hydraulic press, and causing the particles to rearrange and deform under friction against the mold wall, forming a green blank. Chemically, tungsten powder has limited compressibility; adding temporary binders such as paraffin wax strengthens the interparticle bond and improves the strength of the green blank. Unidirectional compression requires lubricating the mold wall to reduce friction, while bidirectional compression improves density uniformity.

Pressure parameter optimization involves load magnitude, pressurization rate, and holding time. High pressure increases density but is prone to delamination, while low pressure results in more porosity. Optimization is determined experimentally, with gradual pressurization to avoid stress concentration. Release agents such as zinc stearate chemical coatings reduce friction and prevent sticking. Green density gradients are mitigated through floating dies or multi-punch designs.

Tungsten alloy sheet blanks of standard thickness, followed by forging or rolling of the smaller blanks. Optimized chemical additive ratios balance strength and thorough degreasing. Gradual pressure release control reduces springback cracking. Variations such as warm die pressing enhance flow, but tungsten alloys are typically processed at room temperature. Environmental control ensures the powder remains dry to prevent moisture absorption.

6.3.3 Application of Injection Molding in Thin Sheet Preforms

Injection molding is used in the production of thin sheet preforms. Tungsten alloy powder is mixed with an organic binder to form a feedstock, which is then injected under high pressure into a mold to form complex or thin-walled green blanks. This method expands the shape freedom of powder metallurgy and is suitable for precision thin sheet preforming. The process begins with the preparation of the feedstock. The powder is mixed with a wax-based or polymer binder at high temperature, and the binder chemically

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encapsulates the particles to improve flowability. After granulation, the feedstock is injected into a heated mold, where pressure pushes it to fill the cavity. Cooling and solidification then demold the blank. Chemical degreasing removes the binder, while solvent or thermal degreasing decomposes organic matter, leaving a porous preform which is then sintered to achieve density.

The advantages of this application lie in near-net-shape forming, uniform thickness of the thin sheet blank, and smooth surface reducing machining. High tungsten loading feed requires optimized viscosity to prevent segregation. Injection parameters such as temperature and pressure must match powder characteristics, and precise mold design is essential for controlling wall thickness.

This application holds great potential in ultra-thin tungsten alloy sheet preforms, enabling the formation of complex shapes such as perforated sheets. The chemical binder is selected with low residual carbon to prevent carbide embrittlement. Slow debinding prevents blistering and cracking. Subsequent sintering shrinkage is controllable. The binder is environmentally recyclable, reducing pollution.

6.3.4 Green body strength enhancement and degreasing process

Improving green body strength and debinding are crucial post-molding processes. Green body strength is enhanced through additives or pre-sintering, while debinding removes temporary binders to ensure defect-free subsequent sintering. Strength enhancement methods include increasing the binder ratio or low-temperature pre-sintering, chemically bridging binder particles, and slight diffusion during pre-sintering to form neck bonds. Molded green body strength depends on pressure, while injection-molded feedstocks have high inherent strength.

Degreasing processes are divided into solvent degreasing and thermal degreasing. Solvent degreasing involves immersing the material in an organic solvent to dissolve the wax base, while thermal degreasing decomposes the polymer through heating. Chemical control of the heating rate prevents rapid vaporization and bubbling. A combined degreasing process, solvent followed by heat, is highly efficient and leaves low residue. Optimized process parameters prevent cracking, and support materials assist in the preparation of the billet. This process is particularly important in injection-molded billets; thorough degreasing affects sintering purity. A balance must be struck between strength enhancement and degreasing; excessively strong bonding makes degreasing difficult. Chemical analysis of residual carbon monitors the degreasing effect. Solvents are recovered through environmental waste gas treatment.

6.4 Sintering Process

Sintering is the core stage in tungsten alloy sheet preparation. Through high-temperature treatment, the formed green billet is transformed into a high-density bulk material, eliminating porosity and forming a stable two-phase microstructure. This process directly determines the material's density, phase distribution, and interfacial bonding strength. Sintering methods include vertical sintering in a hydrogen atmosphere, vacuum sintering, and integrated sintering-hot isostatic pressing (HIP). Hydrogen sintering is suitable for traditional liquid-phase systems, vacuum sintering focuses on impurity control, and

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integrated processes improve the quality of complex billets. The process principles involve solid-phase diffusion, liquid-phase rearrangement, and dissolution-re-precipitation mechanisms. Tungsten particles spheroidize under the wetting of the binder phase, enhancing interfacial chemical bonding. Temperature, atmosphere, and holding parameters must be precisely matched to the alloy system to avoid over-sintering (coarsening) or under-sintering (porosity).

In recent years, sintering optimization has incorporated continuous furnaces and intelligent control to improve uniformity and energy efficiency. The chemical atmosphere plays a significant role, with hydrogen reducing oxides and vacuum removing volatile impurities. The billet loading method affects the temperature field; vertical suspension or boat loading reduces deformation. Cooling rate regulates precipitated phases, with slow cooling promoting uniformity. Defect prevention focuses on blistering and cracking, mitigated through pre-degassing and gradient heating.

6.4.1 Vertical sintering technology in a hydrogen atmosphere

Vertical sintering in a hydrogen atmosphere is a classic method for densifying tungsten alloy sheet billets. Heating in a hydrogen-protected furnace under a molybdenum boat or in a suspended state achieves liquid-phase sintering and impurity reduction. This technology is suitable for mass production of nickel-iron and nickel-copper systems. The process involves placing the green billet vertically or in a boat, with continuous hydrogen flow. The temperature is raised above the liquidus temperature and held, allowing the reduction reaction to remove surface oxides, while water vapor is expelled with the gas flow. Chemically, hydrogen reacts with oxygen to produce water, keeping the billet clean, promoting the wetting of tungsten particles by the binder phase, and facilitating rearrangement and densification. The vertical arrangement reduces contact between the billet and the boat, avoiding adhesion and localized contamination.

The technological advantage lies in the dual effect of the reducing atmosphere, which reduces impurities while providing protection against tungsten oxidation and volatilization. The furnace types are mostly continuous push-boat furnaces or bell-jar furnaces; the former offers high automation, while the latter provides more uniform temperature. The heating curve is segmented: low-temperature degassing removes residual binder, medium-temperature solid-phase diffusion occurs, and high-temperature liquid-phase holding occurs. During the holding period, tungsten particles spheroidize, and the dissolution-re-precipitation mechanism refines the interface. Cooling is controlled at the rate in hydrogen to avoid thermal stress cracking.

This technology is maturely applied in the sintering of high-density tungsten alloy sheets. Strict management of hydrogen dew point ensures sufficient reduction at low dew points and prevents over-reduction at high dew points. Optimized billet spacing ensures uniform airflow and reduces temperature gradients. Chemical purity is improved through multi-stage hydrogen filtration. Variants such as wet hydrogen control moisture and promote oxygen removal. Environmental waste gas treatment neutralizes moisture.

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6.4.2 Control of liquid phase sintering temperature window and holding time

The control of the liquid phase sintering temperature window and holding time is a core parameter in the sintering process of tungsten alloy sheets, directly affecting the amount of liquid phase, particle rearrangement, and microstructure evolution. This control ensures sufficient densification while avoiding abnormal growth. The temperature window is located above the melting point of the binder phase. After the liquid phase appears, a suitable amount flows and wets the tungsten particles, and the reduced surface energy on a chemical level drives rearrangement, dissolving small particles and precipitating them onto the surface of larger particles. A narrow window results in insufficient liquid phase and low density if too low, while excessive liquid phase leads to green body collapse or segregation. The window is higher in nickel-iron systems and lower in nickel-copper systems, requiring adjustment based on the phase diagram.

The holding time controls the degree of reaction in the liquid phase; a short holding time is dominated by rearrangement, while a long holding time is dominated by dissolution-re-precipitation and spheroidization. The optimal holding time was determined experimentally, with rapid densification in the initial stage and slow refinement in the later stage. The heating rate affects the window entry point; a slow heating rate avoids localized overheating. Atmosphere control is used in conjunction; hydrogen flow carries away volatiles, maintaining window stability.

This control varies across billet thicknesses; larger billets have a more conservative heat window to prevent deformation, while smaller billets can have extended heat preservation to promote uniformity. Chemical additives such as cobalt expand the heat window and improve fluidity. Monitoring is achieved through multi-point temperature measurement using thermocouples to ensure consistent temperature within the furnace. Cooling is slow and exits through the heat window to lock in the microstructure. Variations include segmented heat preservation, with a high-to-low stage for optimized heat preservation. Environmental energy management saves on heat preservation time.

6.4.3 Vacuum sintering and sintering-hot isostatic pressing integrated process

Vacuum sintering and sintering-hot isostatic pressing (HIP) are advanced methods for producing high-end tungsten alloy sheet billets. The former removes gaseous impurities through high vacuum, while the latter combines sintering with pressure densification, improving the quality of complex or high-requirement billets. This process is suitable for tungsten-copper pseudo- alloys or high-purity systems. Vacuum sintering involves heating in a vacuum furnace, where negative pressure removes pore gases and volatile impurities, chemically preventing hydrogen residue, maintaining interface cleanliness, and promoting solid-phase or low-liquid-phase diffusion. The temperature is higher than in traditional sintering to compensate for the lack of liquid-phase flow.

The integrated sintering-hot isostatic pressing (HIP) process is completed in a single piece of equipment. First, vacuum sintering pre-densification is performed, followed by argon-filled pressurized hot isostatic pressing, ensuring uniform pressure in all directions to eliminate closed pores. Chemically, high

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temperature and high pressure accelerate diffusion, resulting in close contact between tungsten particles and enhanced interfacial bonding. The process advantage lies in reduced contamination due to single furnace loading, suitable for both encased and unencased billets. This process has great potential in the pretreatment of ultrathin sheet billets, reducing intermediate defects through integration. Vacuum management is crucial; low vacuum prevents volatilization losses. Temperature and pressure curves are linked, with sintering preceding pressurization. High chemical purity makes it suitable for rare earth-doped alloys. Slow cooling under vacuum avoids stress. Variations include rapid hot pressing. Environmental vacuum pump oil return is implemented.

6.4.4 Sintering Deformation Control and Support Tooling Design

Sintering deformation control and support fixture design are crucial aspects of the sintering process for tungsten alloy sheet billets. Proper support and process parameter adjustments reduce gravitational deformation and warping caused by high-temperature softening, ensuring dimensional accuracy and uniform microstructure of the billet. The appearance of the liquid phase during sintering decreases the billet strength, and gravity easily causes sinking or bending. Chemically, the flow of the binder phase exacerbates deformation. Control must begin with the support method and furnace loading posture. High-purity alumina or molybdenum plates are commonly used in support fixture design, as they are resistant to high temperatures and do not deform. Surface coatings prevent adhesion, and chemical coatings such as boron nitride reduce friction and reactions.

Various tooling options are available. Flat billets utilize multi-point support or sand bed filling, with sand particles dispersing stress. Chemically, high-purity quartz sand exhibits good inertness. Vertical suspension is suitable for long billets, with clamps fixing both ends to reduce bending. The design considers thermal expansion matching to avoid thermal stress cracking. Deformation control also involves slow heating rates, thorough degassing at low temperatures, and short holding times during the liquid phase to reduce flow time. Optimization of billet posture, such as tilting to balance gravity, is also employed.

A synergistic chemical atmosphere ensures uniform hydrogen flow and reduces localized softening. During the cooling stage, supports maintain low temperatures to prevent deformation due to thermal stress release. Reusable tooling requires cleaning to remove residue. Variants such as flexible ceramic fiber supports adapt to different shapes. Environmentally friendly material recycling reduces costs.

6.4.5 Ensuring Temperature Uniformity during Sintering of Large -Size Slabs

Uniform temperature field during the sintering of large-sized slabs is crucial for achieving consistent microstructure and density. This is achieved by minimizing temperature gradients through furnace design, loading methods, and heating control, preventing localized over- or under-firing. Large slabs have high heat capacity, making them prone to uneven temperature distribution within the furnace. Chemically, temperature differences affect the timing of liquid phase emergence, leading to inconsistent rearrangement. To address this, the furnace structure is optimized, with independent temperature control

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in multiple heating zones and multi-point thermocouple feedback for power adjustment. Radiation shielding plates distribute heat flow evenly, reducing edge heat loss.

The furnace loading method emphasizes the spacing and position of the billets, with an auxiliary heating element placed in the center and high thermal conductivity material at the bottom for uniform heat transfer. A chemical atmosphere circulates, with hydrogen entering and exiting the stirring furnace through multiple pathways. The heating curve is segmented and gradual, with power balance adjustments made during the holding period. The monitoring system maps the temperature field in real time, pausing adjustments when significant deviations occur.

This kind of assurance is challenging in the sintering of thick slabs, where multi-layered furnace charging requires rotation or flipping for uniform heating. High-purity furnace linings reduce contamination affecting heat radiation. Uniform cooling prevents thermal stress gradients. Variants include induction-assisted heating with localized compensation. Environmental energy management saves energy through multi-zone regulation.

6.5 Heat working and heat treatment

Hot working and heat treatment are the deformation and microstructure control stages of tungsten alloy sheets from sintered billets to finished sheets. Through high-temperature forging, hot rolling, warm rolling, and annealing, thickness reduction and performance optimization are achieved. This process addresses the brittleness of sintered billets and introduces fibrous structures to enhance strength and toughness. The principle of hot working involves dynamic recovery and recrystallization; chemically, high temperatures activate slip systems, and the binder phase coordinates the deformation of tungsten particles. Forging breaks the cast structure, hot rolling reduces thickness through large deformation, and intermediate annealing releases stress and restores plasticity. Heat treatment includes vacuum annealing and aging to adjust grain size and precipitates.

Process optimization focuses on matching temperature windows and deformation amounts. High-temperature processing is easier but requires protection against oxidation, while low-temperature hardening is faster but carries a risk of cracking. Atmosphere control uses hydrogen or vacuum to prevent decarburization or oxygenation. Rolling pass design incorporates progressive reduction, and lubrication reduces surface damage. Uniform furnace temperature during heat treatment is crucial, as the cooling rate affects the microstructure. Defect prevention focuses on edge cracks and delamination, mitigated through cladding or side pressure. In summary, hot working and heat treatment demonstrate the engineering utilization of high-temperature plasticity, providing a deformation path for tungsten alloy sheets from bulk to thin sheets.

6.5.1 Forging and Hot Rolling Process

Forging and hot rolling are the initial stages of hot working of tungsten alloy sheets. High-temperature, large deformation squares or thins the sintered billet, breaking up coarse structures and introducing

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deformation textures, laying the foundation for subsequent cold rolling. Forging commonly uses free forging or die forging. The billet is heated to a high temperature and hammered or pressed under hydrogen protection. Chemically, the high temperature reduces deformation resistance, and the binder phase flows to encapsulate tungsten particles, preventing breakage. Multi-directional forging with alternating directions promotes uniform deformation, and initial fibrous formation of the microstructure is achieved.

Hot rolling follows forging, with multiple passes further thinning the billet. Each pass involves significant reduction, and the rolls are heated or the billet is held at a constant temperature. Chemically, hot rolling results in active dynamic recovery, with dislocation rearrangement reducing hardening accumulation. A protective atmosphere or coating prevents oxidation, and lubricants reduce friction. Reheating between passes restores plasticity. Parameter optimization involves a gradual temperature decrease; high-temperature initial rolling is prone to deformation, while low-temperature finishing ensures a smooth surface.

This process is particularly evident in the production of thick tungsten alloy sheets. High total deformation during forging breaks down sintered porosity, while hot rolling achieves a plate-like shape. Chemical purity management is crucial, and a low atmosphere dew point prevents hydrogen embrittlement. Edge crack control is achieved through rounded corner rolls or side guides. Variations include cladding hot rolling to protect the surface. Environmental waste heat recovery saves energy.

6.5.2 Multi-directional forging improves microstructure uniformity

Multi-directional forging is an effective method for improving the uniformity of microstructure in the hot working of tungsten alloy sheets. By repeatedly changing the deformation direction, it achieves a balanced distribution of internal stress and microstructure in the billet, reducing segregation and porosity left over from sintering. This forging method is widely used in the billet preparation stage. After the billet is heated to a high temperature, it is forged alternately along multiple axes. Chemically, the high temperature activates the coordinated deformation of tungsten particles, and the binder phase flows to fill the gaps, promoting particle rearrangement and breaking up coarse aggregates. Unidirectional forging tends to form directional textures and density gradients, while multi-directional forging disperses segregation through cross-stress fields, making the microstructure more isotropic.

The forging process typically involves several rounds, each changing the direction (e.g., XYZ axis sequence). The total deformation gradually accumulates, and repeated chemical deformation induces dynamic recovery, with dislocation rearrangement reducing localized hardening. Reheating in the furnace between direction changes restores plasticity and prevents cold-working cracks. The process's advantages lie in improving the center uniformity of large billets and reducing the density difference between the edges and the center. Supporting fixtures assist in positioning and prevent asymmetrical deformation.

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This forging process plays a significant role in the production of high-density tungsten alloy sheets, resulting in refined microstructure, increased spheroidization of tungsten particles, and enhanced interfacial bonding. Chemical purity management is crucial, and a protective atmosphere is essential to prevent oxidation and ensure proper deformation coordination. Matching the forging frequency and reduction amount prevents excessive speed that could lead to internal tearing. Variations such as radial-axial combinations can be adapted to different shapes. Environmental waste heat utilization saves energy.

6.5.3 Intermediate Annealing and Stress Relief Heat Treatment

Intermediate annealing and stress-relief heat treatment are necessary interval steps in the hot working sequence of tungsten alloy sheets. These processes, performed under vacuum or a protective atmosphere, release residual stress and work hardening accumulated during rolling, restoring the material's plasticity and preparing it for the next deformation pass. This heat treatment is carried out after hot rolling or between cold rolling passes, with the temperature controlled below or slightly above the recrystallization threshold. Chemically, high-temperature diffusion drives dislocation migration and annihilation, while the softening of the binder phase coordinates stress release from the tungsten particles. Vacuum annealing prevents oxidation, and hydrogen-based processes further reduce the surface.

The annealing process consists of heating, holding, and cooling stages. The holding time allows for sufficient stress relaxation, chemically refining the microstructure through grain boundary migration, and dissolving or homogenizing precipitated phases. Slow cooling prevents the introduction of new stress. The process advantage lies in preventing edge cracks or delamination caused by cumulative hardening, which is crucial for recovery in multi-pass rolling. The temperature window is adjusted according to the alloy system; a higher window is used for nickel-iron alloys to promote recovery.

This heat treatment is frequently used in thin sheet production, involving numerous annealing cycles after large deformation from cold rolling to ensure optimal overall processing efficiency. Chemical atmosphere purity is crucial, with low dew points preventing hydrogen embrittlement. Uniform furnace temperature ensures consistent results across multiple billets. Variations such as gradient annealing optimize surface-to-core differences. Environmental vacuum pump maintenance reduces contamination.

6.5.4 High-temperature solution treatment and rapid cooling

High-temperature solution treatment and rapid cooling are strengthening methods in the heat treatment of tungsten alloy sheets. By dissolving alloying elements at high temperatures and rapidly locking them into a supersaturated state, the strength and high-temperature stability of the material are improved. This treatment is often applied after final hot working or when specific performance requirements are met. Solution treatment involves heating the sheet to above the temperature at which the binder phase is fully dissolved and holding it at that temperature. Chemically, tungsten atoms dissolve into the binder phase in a limited manner, forming a supersaturated solid solution. Diffusion of interfacial elements enhances bonding. The holding period allows for uniform dissolution, avoiding localized segregation.

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Rapid cooling, such as water quenching or gas quenching, freezes the material to a high temperature state, chemically inhibiting precipitation and preserving fine dispersed phases or solid solution strengthening effects. The choice of cooling medium balances quenching stress and oxidation risk; inert gas quenching is gentler. The process advantages lie in improved hardness and heat resistance, with supersaturated binder phases pinning dislocations and increasing strength.

This treatment is applied to wear-resistant or heat-sinkable tungsten alloy sheets, increasing strength after solution treatment but requiring monitoring of toughness. A chemical atmosphere vacuum prevents decarburization. Precise temperature control avoids overheating and coarsening. Variations such as staged cooling optimize stress distribution. Environmental media recycling reduces consumption.

6.6 Cold rolling and warm rolling for sheet preparation

Cold rolling and warm rolling are finishing stages in tungsten alloy sheet production. Through multi-pass rolling at room or medium temperatures, the hot-worked billet is gradually thinned to the target thickness, forming a fine microstructure and excellent surface quality. This process is suitable for preparing sheets ranging from millimeters to micrometers in size. Cold rolling, performed at room temperature, results in significant work hardening and a large total deformation. Warm rolling, on the other hand, aids in recovery within the medium temperature range, reducing the risk of cracking. The process principles involve dislocation multiplication, dynamic recovery, and texture formation. Chemically, the binder phase coordinates tungsten particles during deformation, preventing brittle fracture. The reduction distribution per pass needs to be gradual, with a large initial reduction for shaping and a smaller reduction for finishing in the later stages. Rolling direction and texture control affect anisotropy, and edge management prevents cracking.

Process optimization focuses on lubrication and tension control. Cold rolling uses oil lubrication to reduce friction, while warm rolling uses inert gas protection to prevent oxidation. Intermediate annealing intervals release stress and restore plasticity. Thin sheet production emphasizes mill precision and a high-rigidity rolling system to avoid thickness fluctuations. Defect prevention focuses on cracks and orange peel, which are mitigated through trimming and surface inspection.

6.6.1 Cold Rolling Total Deformation Distribution and Pass Reduction Specification

The allocation of total cold rolling deformation and the pass reduction schedule are the core planning aspects of the tungsten alloy sheet thinning process. By rationally distributing the total processing rate and single-pass reduction, uniform deformation and controllable stress are ensured, preventing cracks and warping. This schedule starts with a hot-rolled billet, where the total deformation is often high to achieve fine grain strengthening and thickness accuracy. The allocation principle is to initially use a larger reduction in each pass to utilize residual thermoplasticity for shaping, and then gradually reduce the reduction in later passes to refine the surface. Chemically, the large reduction activates the multi-slip system, allowing the binder phase to fully flow and encapsulate the tungsten particles, reducing particle breakage. The schedule design considers the material state; the initial cold working hardening is slow,

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allowing for a larger reduction, while the later hardening accumulation requires a smaller reduction and increased annealing intervals. Uniform application of lubricating oil between passes reduces roll friction and chemically prevents roll sticking, which can cause surface scratches. Tension control helps stabilize the sheet shape and prevents center or edge waves. The total deformation is calculated based on the target thickness; ultra-thin sheets require multiple cycles of rolling and annealing.

This process allows for flexible adjustments during the transition from standard thickness to thin sheets, with high-tungsten alloys undergoing conservative rolling to prevent edge cracking. Chemical atmosphere management prevents oxidation of the rolled sheet. The process records pass thickness and adjusts deviations in real time. Variants such as asymmetric rolling optimize sheet shape. Environmentally friendly lubricant recycling reduces pollution.

6.6.2 Application of warm rolling in high-tungsten content alloys

The application of warm rolling in high-tungsten alloys mitigates the brittleness risk associated with room-temperature cold rolling by rolling in the intermediate temperature range. It utilizes moderate heating to activate the recovery mechanism, achieving thinner profiles with large deformation. This application is particularly suitable for alloy systems with high tungsten content. The warm rolling temperature is controlled below the recovery recrystallization temperature. Chemical heating reduces deformation resistance, softens the binder phase to enhance coordination, and reduces the slip resistance of tungsten particles, thus avoiding edge cracks common in cold rolling. The rolling mill is equipped with heating devices or preheats the billet, and inert gas protection prevents oxidation.

The advantages of warm rolling lie in its balanced hardening and recovery, larger reduction per pass compared to cold rolling, higher overall processing efficiency, and reduced annealing times. Chemically, warm rolling exhibits more active dynamic recovery, reducing dislocation rearrangement and accumulation, resulting in surface quality superior to pure cold rolling. The process combines hot rolling transition with cold rolling finishing, forming a hybrid path. High-tungsten alloys have fewer binder phases, and warm rolling expands the deformation window.

This application shows significant potential in ultra-thin, high-density tungsten alloy sheets, producing a fine, fibrous microstructure with balanced strength and toughness after warm rolling. Chemical lubrication ensures high-temperature adaptability, while graphite or special oils prevent sticking. Temperature uniformity is crucial, and induction heating provides rapid response. Variants include roll heating assistance. Environmental exhaust gas extraction ensures safety.

6.6.3 Rolling Direction Control and Texture Optimization

Rolling direction control and texture optimization are microstructure control methods in the cold and warm rolling processes of tungsten alloy sheets. By adjusting the deformation texture and crystal orientation through unidirectional, cross, or multidirectional rolling paths, the anisotropy and performance balance of the material are affected. This optimization helps to achieve directional control

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of strength, toughness, and thermal expansion. Unidirectional rolling forms a strong fibrous texture, elongates tungsten particles along the rolling direction, and produces a preferred orientation due to the planar stacking of chemical dislocations, increasing longitudinal strength but reducing transverse toughness. Cross rolling rotates 90 degrees in each pass, breaking up the orientation, and weakening the texture to a more random state.

Optimization principles are selected based on the application. Shielding sheets require isotropic cross-rolling, while structural components with longitudinal strength require unidirectional rolling. Multidirectional variants, such as pendulum rolling, further homogenize the material. Chemically, texture affects the distribution of interphase stress; optimization reduces residual heat treatment. Annealing, combined with other methods, controls texture strength; high-temperature annealing weakens it, while low-temperature annealing retains it. This control and optimization has a significant impact on sheet production; ultrathin foils with strong textures are prone to bending and cracking, which is improved through cross-optimization. Chemical analysis using X-ray diffraction pole figures assesses orientation density. Orientation markings facilitate downstream use of the finished product. Variations include oblique rolling for special textures. Environmentally friendly roller systems are used for cleaning and scratch prevention.

6.6.4 Edge Crack Prevention and Trimming Process

Edge crack prevention and trimming are crucial defect management aspects in tungsten alloy sheet rolling. Adjusting rolling parameters, protecting edges, and regularly trimming reduce crack initiation and propagation, ensuring sheet integrity and yield. Edge cracks originate from stress concentration, chemically resulting from high edge shear in tungsten particles and insufficient bonding phase coordination. Preventive measures include gradually decreasing rolling pressure per pass, smooth edge transitions, and using side guide rolls to constrain sheet shape and prevent edge waviness from inducing tensile stress.

Trimming processes use shearing machines or wheel cutters to periodically remove cracked edges, and chemical cleaning of the cut surfaces prevents secondary cracking. Prevention also involves uniform lubrication and applying extra coating to the edges to prevent dry friction. Warm rolling reduces crack susceptibility, while cold rolling monitors hardening accumulation and anneals promptly.

This prevention and trimming process is frequently used in thin sheet rolling, where cracks easily propagate in the ultra-thin stage, necessitating short trimming intervals. Chemical surface inspection is aided by fluorescent penetrant testing. Trimming waste is recycled and pulverized. Variants such as laser trimming offer precise, burr-free finishes. Environmentally friendly cutting fluid filtration ensures safety.

6.7 Surface Treatment and Finishing

Surface treatment and finishing are the final stages of tungsten alloy sheet production. Methods such as chemical cleaning, machining, and thermal leveling remove surface defects, improve flatness and

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smoothness, and enhance the material's appearance, corrosion resistance, and functional adaptability. This process directly affects the surface integrity and bonding performance of the sheet in precision applications. Surface treatment targets oxide layers, enriched phases, and rough surfaces left over from rolling or heat treatment, while finishing achieves dimensional accuracy and edge quality. The process principles involve chemical dissolution, mechanical removal, and thermal stress release. Chemical treatment offers high selectivity, mechanical treatment offers high efficiency, and thermal leveling combines the advantages of both. The processing sequence typically involves cleaning and decontamination first, followed by polishing, and finally cutting to length.

The finishing process prioritizes non-destructive and cleanliness. Chemical cleaning avoids residual corrosion, mechanical polishing controls particle embedding, and vacuum thermal leveling prevents re-oxidation. Laser or waterjet cutting achieves complex shapes and reduces the heat-affected zone. Quality control includes surface roughness measurement and visual inspection to ensure Ra value and the absence of cracks. Environmental considerations include waste liquid neutralization and recycling, and safe dust collection.

6.7.1 Chemical cleaning and acid pickling to remove oxide layer

Chemical cleaning and acid pickling to remove the oxide layer are the primary steps in the surface treatment of tungsten alloy sheets. Acidic solutions dissolve and remove the oxide scale and dirt formed during rolling or heat treatment, restoring the metallic luster and providing a clean substrate for subsequent processing. This method selectively dissolves oxides with minimal damage to the substrate. The cleaning process begins with alkaline washing to remove oil, followed by acid pickling to primarily remove oxides. Chemically, the oxide layer mainly consists of tungsten oxide and binder oxides, which are effectively dissolved by mixtures of nitric acid, hydrofluoric acid, or sulfuric acid, allowing the tungsten to form complexes that enter the solution. The pickling time and temperature are carefully controlled to avoid over-etching, which can lead to surface pitting or hydrogen embrittlement.

The process's advantages lie in its efficient removal of thin oxide layers, suitability for sheets of various thicknesses, and chemical formulation adjustments based on the alloy system. In nickel-copper systems, the low acid concentration prevents excessive copper dissolution. After cleaning, water rinsing and neutralization are followed by passivation to form a temporary protective film. Waste liquid treatment involves neutralization and recovery of fluoride ions or nitrates. This cleaning method is widely used in hot-rolled sheets. Removing thick oxide scale improves surface activity, facilitating polishing or plating. Chemical monitoring of pH and concentration ensures batch consistency. Variants such as ultrasonic-assisted dissolution accelerate the process. A closed-loop environmental system reduces emissions.

6.7.2 Alkali washing removes surface enrichment of the binder phase

Alkaline washing to remove surface enrichment of the binder phase is a targeted surface treatment method for tungsten alloy sheets. It selectively dissolves the surface enrichment of the binder phase caused by rolling or heat treatment using an alkaline solution, balancing the surface composition and

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improving corrosion resistance. This method is applied in alloys with high binder phases to avoid preferential corrosion of the enriched layer. The cleaning process involves immersion in a hot solution of sodium hydroxide or sodium carbonate. Chemically, the alkali reacts with nickel or copper oxides to form soluble salts, while the inert tungsten phase remains largely insoluble. The surface enriched layer is then thinly removed, exposing the balanced substrate.

The process offers advantages such as high selectivity, minimal damage to the tungsten framework, and suitability for non-magnetic or thermally conductive sheets. Precise temperature and time control accelerate dissolution while preventing excessive pitting. After cleaning, residual alkali is neutralized with acid, followed by rinsing and drying. Auxiliary stirring or ultrasonication enhances uniformity. This alkaline washing is particularly effective in nickel-copper system sheets, where copper tends to accumulate on the rolled surface, resulting in uniform conductivity after washing. Chemical analysis of the surface composition verifies the removal effect. Variations such as electrolytic alkaline washing accelerate the process. Environmental alkaline solution regeneration and recycling are also possible.

6.7.3 Mechanical Grinding and Polishing

Mechanical grinding and polishing are the core methods for finishing the surface of tungsten alloy sheets. By using abrasive belts, grinding wheels, or polishing paste, surface roughness and defects are gradually removed to achieve high smoothness and low roughness. This method is suitable for sheets of various thicknesses, improving both appearance and functional surface quality. Grinding begins with rough grinding to remove oxide marks and ripples, followed by progressively finer grinding with abrasive belts or grinding wheels. Chemical and mechanical shearing removes material; due to tungsten's high hardness, diamond or boron carbide abrasives are required. Polishing uses a soft cloth wheel with polishing paste, and fine friction produces a mirror finish.

The process offers controllable precision, with a gradually decreasing Ra value, suitable for both flat and curved surfaces. Dry or wet grinding is available, with wet grinding using cooling to prevent heat damage. Grading is performed from coarse to fine, with intermediate cleaning to prevent particle embedding. This grinding and polishing technique is ideal for high-precision medical collimator plates, reducing scattering in the mirror finish. Polishing after chemical cleaning prevents residue buildup. Variations include vibratory polishing for uniformly shaping complex shapes. Environmental dust collection is safe.

6.7.4 Vacuum/Hydrogen-Protected Thermal Leveling Process

leveling thin tungsten alloy sheets. It releases residual stress under a protective atmosphere through high-temperature tension or rolling, improving sheet flatness and dimensional stability. This process is suitable for easily warped thin sheets. The process involves heating the sheet to its stress-relief temperature in a vacuum or hydrogen furnace, applying slight tension, or passing it through leveling rollers. Chemically, high-temperature diffusion relaxes dislocations, softening the binder phase and coordinating deformation. Vacuum prevents oxidation, while hydrogen reduces the surface.

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The advantages lie in its non-contact or minimal-contact nature, resulting in a flawless surface and high flatness. Temperatures below recrystallization levels prevent structural changes. Uniform tension control prevents localized stretching. This process is widely used in ultra-thin tungsten alloy sheets, where warpage after cold rolling is corrected through hot leveling. Chemical purity is crucial, and a low dew point prevents hydrogen embrittlement. Variations include continuous furnace tension leveling. It offers an airtight and energy-efficient environment.

6.7.5 Precision shearing, laser cutting and waterjet cutting

Precision shearing, laser cutting, and waterjet cutting are methods for precision machining of tungsten alloy sheets, including dimensional and irregular shapes. These methods utilize mechanical blades, laser beams, or high-pressure water jets to achieve clean edges and complex shapes, meeting diverse downstream size requirements. Precision shearing uses high-precision shearing machines with sharp cutting edges, resulting in chemically concentrated shear force fracture. It is suitable for straight-edged rectangular sheets, and the adjustable gap prevents burrs.

Laser cutting uses a high-energy laser to melt and vaporize materials, followed by inert gas slag removal. Chemically, it has a small heat-affected zone, making it suitable for complex contours and holes. Power density control allows for narrow kerfs. Waterjet cutting uses a high-pressure water-mixed abrasive jet, resulting in cold cutting without thermal deformation and purely mechanical abrasion, suitable for thick sheets or thermistorous alloys. This cutting method is flexible in custom tungsten alloy sheets, producing precision laser holes and stress-free waterjet edges. Chemical cleaning after cutting prevents contamination. Variants such as fiber lasers can increase speed. Environmental waste is safe to recycle.



CTIA GROUP LTD Tungsten Alloy Sheets

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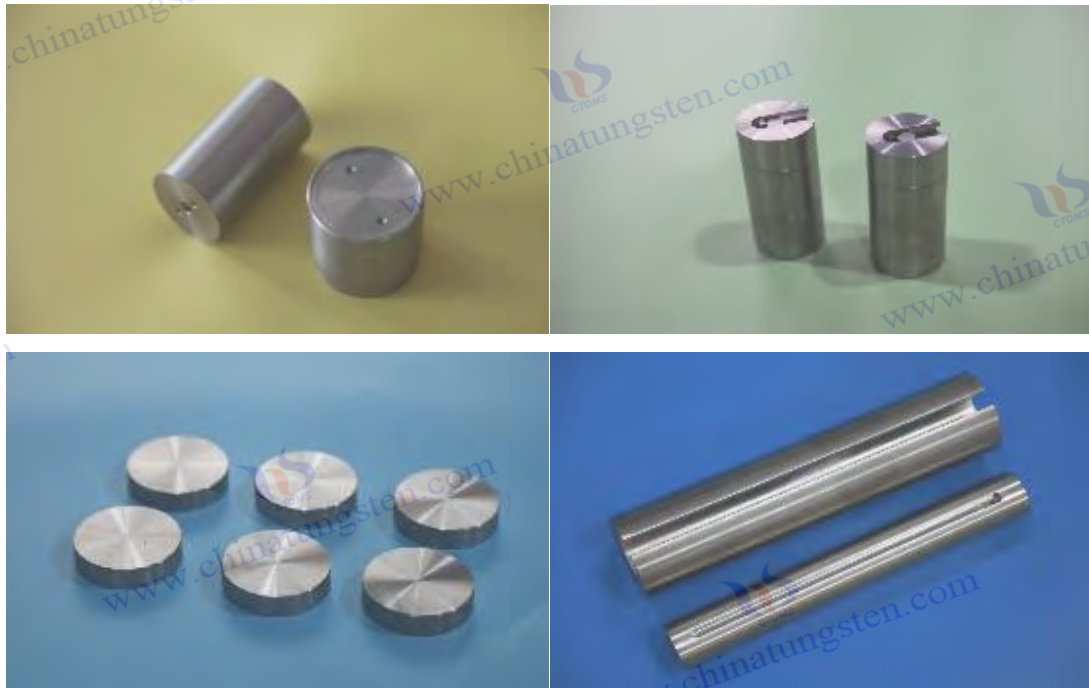
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Chapter 7 Application of Tungsten Alloy Sheets

7.1 Application of Tungsten Alloy Sheets in the Defense and Military Industry

Tungsten alloy sheets are primarily used in the defense and military industries for components requiring high density, high strength, and good toughness. Their high melting point and wear resistance ensure stable performance in harsh environments. Applications include counterweights and protective structures, with functional integration achieved through processing.

7.1.1 Tungsten alloy sheet for armor-piercing

Tungsten alloy sheets in armor-piercing components utilize high density and self-sharpening properties to provide kinetic energy concentration and penetration capability. The alloy design balances hardness and toughness, and the finished surface provides high-speed stability.

7.1.2 Tungsten alloy sheet for counterweight

Tungsten alloy sheets are used as counterweight materials, utilizing high density to achieve weight adjustment within a limited space, helping to balance inertia and control vibration. Uniform thickness ensures accuracy, and surface treatment enhances durability.

7.1.3 Tungsten alloy sheet for protection

Tungsten alloy sheets play a role in radiation attenuation and impact absorption in protective structures, providing high-density, thin-layer, highly efficient shielding. The composite design enhances overall strength and is suitable for multi-layer protective systems.

7.2 Application of Tungsten Alloy Sheets in High-End Manufacturing

Tungsten alloy sheets in high-end manufacturing is mainly due to their combined characteristics of high density, high hardness, and good machinability. These applications cover mold making, cutting tools, and precision mechanical components, helping to achieve design goals of miniaturization, high reliability, and long service life. Tungsten alloy sheets achieve a uniform microstructure through powder metallurgy and precision rolling, providing wear resistance and resistance to high-temperature softening in mold inserts, offering hard support in cutting tools, and utilizing their density advantage to adjust mass distribution in mechanical counterweights. In application, tungsten alloy sheets are often combined with other materials or surface-treated to further expand their functional boundaries.

High-end manufacturing demands a high degree of balance in material properties, and tungsten alloy sheets excel in high-stress, high-temperature, or high-precision applications due to their high elastic modulus and thermal stability. As manufacturing moves towards intelligent and lightweight designs, the application of tungsten alloy sheets is expanding from traditional molds to additive manufacturing

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supports and precision instrument components. Surface coatings or heat treatments can further optimize their corrosion resistance and bonding properties to meet complex operating conditions. Tungsten alloy sheets are available in various thicknesses, with thinner sheets used for precision inlay and thicker sheets suitable for structural support.

7.2.1 Tungsten alloy sheet for mold inserts

Tungsten alloy sheets in mold inserts stems from their high hardness, wear resistance, and resistance to high-temperature softening. This application is widely seen in plastic injection molds, die-casting molds, and glass hot-press molds, helping to extend mold life and improve product quality. As the core working part of the mold, the mold insert withstands repeated high temperatures, high pressures, and wear. Tungsten alloy sheets, embedded in the mold body, provide locally highly wear-resistant areas, reducing overall mold material consumption. The two-phase structure of the tungsten alloy sheet plays a crucial role in the insert; tungsten particles act as the hard phase to resist abrasive erosion, while the binder phase provides a certain degree of toughness to prevent brittle fracture.

In plastic injection molds, tungsten alloy sheets are commonly used at cavity edges or gate areas to withstand the impact and thermal cycling of molten plastic. Surface polishing reduces the tendency to stick to the mold and improves demolding efficiency. In die-casting mold applications, inserts face high-speed impacts and high-temperature corrosion from molten metal; the thermal stability of tungsten alloy sheets helps maintain dimensional accuracy and reduces thermal fatigue cracks. In glass hot press molds, their low thermal expansion and high hardness ensure shape fidelity during the molding of precision optical components. In insert design, tungsten alloy sheets are bonded to the mold steel via brazing, inlaying, or screw fixing; interface treatments such as nickel plating enhance adhesion.

Applications have expanded to high-precision stamping dies. Tungsten alloy inserts are used in the molding of mobile phone frames or electronic connectors to resist repeated stamping of stainless steel or titanium alloy sheets. A surface hardness gradient design balances wear resistance and chipping resistance. In recent years, with the rapid development of electric vehicles and consumer electronics, the demand for long-life dies has driven the development of tungsten alloy inserts towards nanocrystalline or dispersion-strengthened materials, further improving fatigue resistance. Surface coatings such as DLC or TiAlN are common, forming a hard film through chemical vapor deposition, which works synergistically with the substrate for wear resistance. The thickness of the tungsten alloy insert is selected according to the die size; thinner inserts are used in micro-dies, while thicker inserts support large loads.

The processing technology affects the application effect; precision grinding ensures the flatness of the inserts, and heat treatment adjusts the hardness distribution. During mold maintenance, tungsten alloy sheets are easy to replace locally, reducing overall costs. In terms of environmental adaptability, the inserts remain stable in high-temperature oil lubrication or water-based coolants. The application of tungsten alloy sheets also promotes modular mold design, and standardized insert specifications facilitate inventory management.

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7.2.2 Tungsten alloy sheets for cutting tools

Tungsten alloy sheets are primarily used in cutting tools as a substrate or insert, leveraging their high hardness and thermal stability to provide cutting support. This application is seen in certain specialized cutting tools and wear-resistant inserts, helping to handle difficult-to-machine materials or high-temperature conditions. In tool design, tungsten alloy sheets are often combined with cemented carbide or ceramics to form a hybrid structure. The tungsten alloy provides a tough base, while a hard layer is welded or brazed to the surface, improving overall tool life. The density advantage of tungsten alloy sheets helps to balance and reduce vibration in rotating tools.

In turning or milling tools, tungsten alloy inserts are used in tool holders or tool supports to withstand cutting forces and thermal loads. The bonded phase coordinates deformation and absorbs impact, preventing chipping of the tool tip. Chemical stability makes the tool resistant to corrosion in coolant environments, and surface treatments such as electroless plating provide further protection. Applications extend to woodworking or composite material machining tools, where tungsten alloy inserts resist fiber abrasion and maintain a sharp cutting edge.

Tungsten alloy sheets are also used in bushings for certain wire drawing dies or extrusion tools, where tungsten alloy rings or sheets are inlaid in the inner hole to resist metal flow abrasion. Thickness is selected based on the tool body shape; thinner sheets are used for light-load precision tools, while thicker sheets support heavy-duty cutting. Surface texturing, such as laser microstructure processing, improves chip removal performance. The role of tungsten alloy sheets in cutting tools promotes multi-material composite design, and brazing interfaces optimize bonding strength.

In recent years, with the increase in difficult-to-cut materials, tungsten alloy sheets have evolved towards a gradient structure, with a hard surface and a tough core. Heat treatment adjusts the hardness distribution of the cutting tool, and solution strengthening enhances heat resistance. During tool regrinding, the tungsten alloy matrix supports multiple sharpening operations. In terms of environmental adaptability, it remains stable during dry cutting or with minimal lubrication.

7.2.3 Tungsten alloy sheets for mechanical counterweights

Tungsten alloy sheets in mechanical counterweights leverage their high density to achieve mass concentration within a limited space, helping precision machinery adjust its center of gravity, balance inertia, and reduce vibration. This application is commonly found in analytical instruments, inertial navigation devices, and optical platforms. The counterweight sheets are precision-machined into specific shapes and embedded or bonded to the mechanical structure. The uniform density of the tungsten alloy sheets ensures controllable mass distribution, preventing localized deviations from affecting system stability.

In analytical balances or centrifuges, tungsten alloy sheets are used as weights or counterweights. Their uniform thickness allows for fine-tuning, and the surface coating prevents oxidation from affecting mass.

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In inertial instruments, counterweights adjust rotational inertia; the machinability of tungsten alloy sheets allows for complex geometries, meeting miniaturization requirements. Optical instrument platforms utilize counterweights for vibration damping; high-density sheets lower the center of gravity and improve shock resistance.

Tungsten alloy sheets has also expanded to high-speed rotating machinery, such as gyroscopes or motor rotors, where counterweight balancing reduces eccentric vibration and extends bearing life. A wide range of thicknesses are available, with thin sheets for micro-devices and thicker sheets for large-scale mass adjustment. Surface treatments such as gold plating enhance appearance and corrosion resistance, while chemical stability ensures consistent quality over long periods.

The processing technology affects the accuracy of the application; precision shearing ensures smooth edges, and thermal flattening maintains flatness. The role of tungsten alloy sheets in counterweights promotes compact mechanical design, and high-density replacement of traditional materials reduces volume. In terms of environmental adaptability, it exhibits dimensional stability under temperature variations, supporting wide-range temperature operation.

7.3 Applications of Tungsten Alloy Sheets in Nuclear and Medical Fields

Tungsten alloy sheets in the nuclear and medical fields primarily leverages their high density, excellent radiation attenuation capabilities, and biocompatibility. These applications encompass nuclear facility shielding, medical radiotherapy equipment, and nuclear environment components, helping to achieve radiation protection and improved treatment precision. Tungsten alloy sheets offer the advantage of effective shielding thickness through their high tungsten content, resulting in a smaller volume compared to traditional materials, making them suitable for space-constrained applications. In nuclear shielding applications, tungsten alloy sheets are used in container linings or collimation structures, while in the medical field they are frequently found in multi-leaf collimators and protective equipment. Nuclear environment components utilize their thermal stability and radiation tolerance.

Application design emphasizes thickness uniformity and surface smoothness; thin sheets are used for precision collimation, while thicker sheets support the structure. Surface treatments such as coatings enhance corrosion resistance, and composite structures combined with polymers extend flexible shielding. The machinability of tungsten alloy sheets allows for complex molding to meet customized needs. With the development of nuclear medicine and radiotherapy technologies, the application of tungsten alloy sheets is expanding from traditional shielding to functional integration, such as combining with sensors or cooling channels. Biocompatibility ensures safety in medical applications, and tissue stability under radiation supports long-term use.

7.3.1 Tungsten alloy sheets for nuclear shielding

Tungsten alloy sheets in nuclear shielding stems from their high attenuation capabilities for gamma rays and neutrons. This application is commonly seen in the linings of containers in nuclear facilities, the

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inner walls of transport vessels, and the shielding of experimental equipment, helping to reduce radiation leakage and protect the operating environment. The high density of tungsten alloy sheets allows for effective shielding with limited thickness, resulting in significant volume savings compared to other materials and making them suitable for modular designs. In shielding structures, tungsten alloy sheets are fixed through lamination or mirror-mounting, and surface treatments enhance their resistance to radiation oxidation.

In nuclear waste storage containers, tungsten alloy sheets serve as linings to absorb high-energy radiation, maintaining thermal stability over long periods. Experimental setups, such as reactor perimeter shielding walls, utilize tungsten alloy plates, with thickness adjusted according to radiation intensity; uniform microstructure ensures consistent attenuation. The machinability of tungsten alloy sheets allows for irregular cutting, adapting to complex geometries. In composite applications, combining with boride materials enhances neutron absorption, exhibiting good chemical compatibility and no harmful reactions. Applications extend to nuclear fuel processing equipment, where tungsten alloy sheets shield operating windows or robotic arm components, providing radiation tolerance to withstand repeated exposures. Surface coatings, such as nickel, protect the bonding phase, extending service life. The role of tungsten alloy sheets in nuclear shielding promotes facility miniaturization, weight optimization, and ease of transport. In terms of environmental adaptability, they exhibit dimensional stability under high-temperature radiation.

7.3.2 Tungsten alloy sheet for medical shielding

Tungsten alloy sheets in medical shielding is mainly seen in radiotherapy equipment and protective gear. Utilizing their attenuation properties for X-rays and gamma rays, they provide precise radiation shaping and personnel protection, improving treatment positioning and safety levels. The most typical example of medical shielding is the multi-leaf collimator blades of linear accelerators. Layers of tungsten alloy sheets are stacked and move independently to form the beam profile. Uniform thickness ensures sharp edges and reduces the penumbra.

In radiological diagnostic equipment such as CT scanners, tungsten alloy sheets are used in detector collimation grids or anti-scattering plates to absorb stray radiation and improve image clarity. In protective equipment such as radiologist aprons or shielding curtains, tungsten alloy sheets are composited with polymers to form flexible materials, offering lightweight comfort as a replacement for traditional heavy materials. The biocompatibility and non-toxicity of tungsten alloy sheets ensure safe medical contact.

The application design prioritizes precision; polished blade surfaces reduce friction and ensure smooth movement. The thermal stability of the tungsten alloy sheets allows them to maintain their shape under high-dose radiation, while their chemical inertness prevents coolant corrosion. Customized thicknesses cater to different energies of radiation: thin sheets for low-energy X-rays and thicker sheets for high-energy gamma rays. Composite structures are extended to wearable protection, with uniformly distributed tungsten alloy micro-sheets providing comprehensive coverage.

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7.3.3 Tungsten alloy sheets for nuclear environments

Tungsten alloy sheets in nuclear environments leverages their radiation resistance and thermomechanical stability. These applications are found in internal components of nuclear facilities, such as heat sinks, support structures, or localized shielding, helping to maintain reliable operation of equipment under radiation and high-temperature conditions. Nuclear environment components are subjected to neutron and gamma radiation and temperature cycling; the microstructure stability of tungsten alloy sheets reduces swelling and embrittlement, and the binder phase harmonizes stress distribution.

In nuclear reactors or accelerators, tungsten alloy sheets are used as target backplates or cooling channel liners, their thermal conductivity aiding in heat dissipation and maintaining dimensional stability under radiation. Support structures such as mounting brackets utilize high strength to withstand vibration and thermal loads. The machinability of tungsten alloy sheets allows for precision forming, making them suitable for installation in confined spaces.

Applications extend to nuclear instrument components, where tungsten alloy sheets serve as absorbers or collimating windows, combining radiation attenuation with thermal management. Surface treatments enhance oxidation resistance, and coatings protect against long-term exposure. The role of tungsten alloy sheets in nuclear environments promotes equipment durability and reduces maintenance frequency. Chemical stability protects against media reactions.

7.4 Applications of Tungsten Alloy Sheets in the Electronics and New Energy Fields

Tungsten alloy sheets in the electronics and new energy fields mainly relies on their excellent thermal and electrical conductivity, matching coefficient of thermal expansion, and high density. These applications cover power device heat dissipation, electronic packaging, and electrode materials, helping to achieve device miniaturization, high reliability, and efficient energy conversion. Tungsten alloy sheets, through tungsten-copper or tungsten-nickel-copper systems, provide thermal expansion behavior similar to semiconductor materials, reducing thermal stress failure. In heat dissipation substrates, they act as heat sinks to spread heat; in packaging, they serve as shells or transition layers; and in electrodes, they provide resistance to arc erosion. With the rapid development of 5G communication, high-power electronics, and new energy battery technologies, the application of tungsten alloy sheets has expanded from traditional vacuum devices to high-frequency modules and energy storage systems.

The electronics industry demands stringent thermal management ; tungsten alloy sheets, with their high thermal conductivity, facilitate heat diffusion, while surface coatings enhance solderability. In new energy applications, their stability supports high-temperature or cyclic conditions. Tungsten alloy sheets offer flexible thickness options, with thin sheets used in microelectronics and thicker sheets supporting high power. Composite structures are common, combining with ceramics or diamond to enhance performance. The application of tungsten alloy sheets also promotes device integration, with matching thermal interface materials reducing contact thermal resistance. In terms of environmental adaptability, tungsten alloy sheets maintain stable performance across a wide temperature range . In summary, this

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application demonstrates the thermoelectric function of tungsten alloy sheets in electronic new energy, driving improvements in device efficiency and lifespan through performance combinations, and supporting continuous technological advancements in the industry.

7.4.1 Tungsten alloy sheet for heat dissipation substrate

Tungsten alloy sheets in heat dissipation substrates primarily leverages the high thermal conductivity of the tungsten-copper system and its compatibility with the thermal expansion of semiconductor materials. This application is common in high-power LEDs, lasers, and RF modules, helping to quickly dissipate heat and reduce thermal stress cracking. As an interlayer between the chip and the heat sink, the tungsten alloy sheet provides a flat support surface, and nickel-gold plating enhances solderability and provides high chemical bonding strength. In the tungsten-copper pseudo- alloy structure, the copper phase forms continuous thermal channels, while the tungsten framework controls expansion, matching silicon or gallium arsenide substrates.

In power amplifier modules, tungsten alloy substrates support the chip, with thermal conductivity supporting heat accumulation and dispersion during high-frequency operation, and uniform thickness ensuring flatness and reducing warpage. In laser diode applications, the substrate absorbs pump heat, and the thermal capacity of the tungsten alloy sheet buffers instantaneous peak values. In LED packaging, expanding to high-power lighting, tungsten alloy sheets replace traditional copper-molybdenum sheets, offering superior volumetric thermal management .

Application design emphasizes interface treatment, using brazing or sintering to connect chips, and chemical compatibility to avoid reactive layers. Laser processing of surface microstructures increases contact area and improves thermal conductivity. The role of tungsten alloy sheets in the heat dissipation substrate promotes device miniaturization and reliable operation at high power densities. Composite variants with diamond particles enhance thermal conductivity, further extending the limits. In terms of environmental adaptability, it exhibits stable performance under high and low temperature cycling.

7.4.2 Tungsten alloy sheets for electronic packaging

Tungsten alloy sheets are used in electronic packaging to leverage their thermal expansion matching and high-density properties, serving as housings, covers, or transition layers to provide hermetic protection and thermal paths. This application is seen in high-reliability microwave devices and sensor packaging, helping to maintain an internal vacuum or inert gas environment. Tungsten alloy sheets are compatible with ceramic or glass sealing, their chemical stability supports high-temperature brazing, and their coefficient of thermal expansion is close to reduce sealing stress.

In power semiconductor packaging, tungsten alloy sheets serve as bases or leadframe transitions, conducting heat away from junction heat while reducing overall weight due to their density advantage. In microwave tube packaging applications, tungsten alloy cover plates ensure electromagnetic shielding,

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and their high density enhances structural rigidity. Sensor housings utilize tungsten alloy sheets for environmental corrosion resistance, and surface coatings improve solderability.

7.4.3 Tungsten alloy sheet for electrodes

Tungsten alloy sheets in electrodes mainly leverages their resistance to arc erosion and high conductivity. This application is seen in high-voltage switches, resistance welding electrodes, and certain discharge tubes, helping to extend contact life and maintain stable conductivity. As contact surfaces or inserts, the tungsten phase resists welding, while the copper or silver phase provides a conductive path. Chemically, the ablation products volatilize and carry away thermal damage.

In resistance welding electrodes, tungsten alloy sheets are embedded in a copper substrate to withstand repeated spot welding impacts. Their high hardness reduces deformation, while their conductivity supports high currents. In vacuum switch applications, the tungsten alloy electrode faces the electric arc, its ablation resistance maintains a smooth contact surface, and reduces material transfer.

Applications have expanded to electrical discharge machining electrodes. Tungsten alloy sheets reduce wear and improve processing efficiency, while optimized surface texture ensures uniform discharge. The discharge tube electrodes utilize tungsten alloys that withstand high-voltage breakdown, and their stability supports repeated discharges.

Tungsten alloy sheets in the electrodes promotes contact reliability and lifespan, while the composite design balances conductivity and wear resistance. Thickness is determined according to current level; thinner sheets provide precision contact, while thicker sheets offer heavy-duty support. Surface polishing reduces initial resistance.

7.5 Application of Tungsten Alloy Sheets in Cards

Tungsten alloy sheets in cards primarily leverages their high density, resulting in a substantial feel and metallic luster, along with excellent processability and wear resistance. This application combines functional materials with everyday items, giving cards a unique texture and durability. Tungsten alloy sheets are precision rolled into thin foils or composite layers, then laminated with plastic or metal substrates. Thickness control ensures compatibility with standard card sizes. Applications cover bank payment cards, pet identification tags, and commemorative holiday cards, meeting consumer demand for high-end, personalized, and long-lasting products.

Tungsten alloy sheets provide anti-counterfeiting textures and visual effects in cards. Polished or brushed surfaces enhance aesthetics, while plating such as gold or black titanium adds color variety. Chemical stability makes the cards resistant to daily wear and corrosion, maintaining their shine for a long time. In the composite process, the tungsten alloy layer is hot-pressed to a PVC or PC substrate, with adhesives ensuring interlayer strength. The application of tungsten alloys also facilitates lightweight card designs, achieving a sense of weight without increasing volume through high-density, thin layers. With the

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upgrading of consumption, tungsten alloy cards have expanded from luxury goods to personalized gifts, with processing technologies such as laser engraving supporting customized designs. In terms of environmental adaptability, the cards are resistant to bending and high temperatures.

7.5.1 Tungsten Alloy Bank Cards and Payment Cards

Tungsten alloy bank cards and payment cards are high-end payment tools that incorporate thin tungsten alloy sheets into the card body. These cards provide a metallic weight and cool touch through the tungsten alloy layer, distinguishing them from traditional plastic cards and enhancing the holder's sense of identity and user experience. The tungsten alloy sheet is typically rolled into an extremely thin foil, then hot-pressed together with multiple layers of plastic substrate, and covered with a transparent protective layer. The chemical inertness of the tungsten alloy ensures that the card will not fade or deform under daily friction and bending. The standard card size is compatible with existing card readers, and the embedded chip and magnetic stripe do not affect functionality.

Tungsten alloy bank cards are often issued by financial institutions as high-end memberships or black cards. Their weight adds a sense of ceremony when withdrawing them, while the metallic luster enhances visual appeal. Various surface treatments are available, including brushed textures and mirror polishing, with laser engraving of the card number and design, providing excellent anti-counterfeiting features. The thickness of the tungsten alloy layer is finely adjusted to balance weight and flexibility, and bending tests ensure no delamination. Chemical plating options such as rose gold or gunmetal offer color choices to meet individual preferences.

Payment card applications are expanding to contactless payments. Tungsten alloys do not interfere with radio frequency signals, and the antenna layer design is compatible. Their abrasion resistance keeps the cards looking new even with wallet friction, and their long lifespan reduces replacement frequency. The processing technology for tungsten alloy cards is mature, resulting in precision-cut edges that are smooth and burr-free after lamination. In terms of environmental adaptability, the cards are resistant to high temperatures and chemical cleaning agents, making them suitable for global use. The application of tungsten alloys also advances card anti-counterfeiting technology; their unique density makes them difficult to imitate.

7.5.2 Tungsten Alloy Pet Identification Tag

Tungsten alloy pet identification tags are small tags made from thin sheets of tungsten alloy, used for identifying pets by their collars. These tags offer a combination of durability and aesthetics through their high density and metallic texture, resisting wear and corrosion from pet activity. The tungsten alloy sheets are rolled into thin sheets and then stamped into various shapes such as bones, round tags, or hearts. The surface is laser-engraved with the owner's information and the pet's name; the chemical hardness of the tungsten alloy ensures the engraving is deep, durable, and does not become blurred.

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Pet identification tag applications , tungsten alloy offers a moderate weight, minimizing burden on pets, while the clasp design ensures a secure fit and prevents detachment. Polished or brushed surfaces reflect light, enhancing visibility, and plating options such as black rhodium or gold provide a variety of color choices. Chemical stability ensures the tag remains intact even in outdoor rain, mud, or from pet licking, without rusting or fading. The controlled thickness ensures it is thin yet strong, resisting bending and cracking.

The application has expanded to the high-end pet supplies market, with tungsten alloy plates serving as luxury accessories. These plates are paired with leather collars and feature custom designs including pet photo outlines or QR code links . Their durability allows for long-term wear by active pets, and the clear information facilitates retrieval if lost. The machinability of the tungsten alloy plates allows for small-batch personalization, and the rounded edges prevent injury to the pet's skin.

7.5.3 Tungsten Alloy Holiday and Commemorative Customized Cards

Tungsten alloy holiday and commemorative custom cards are made from thin tungsten alloy sheets and served as holiday gifts or souvenirs. These cards convey special emotions and collectible value through their metallic weight and permanent luster, distinguishing them from paper or plastic cards. Made from composite or pure metal tungsten alloy sheets, the surface is laser-engraved with greetings, dates, or designs. The chemical stability of tungsten alloy ensures the information will never fade, making them suitable for long-term preservation.

For holiday card applications, such as birthdays, anniversaries, or holiday greeting cards, tungsten alloy provides a substantial feel and a delightful surprise when removed, with plating colors like gold or silver matching the holiday theme. Commemorative cards are used for weddings, graduations, or corporate milestones, with custom shapes like hearts or bookmarks, and inlaid gemstones or embossed designs enhancing their artistic appeal. Thin yet sturdy, they are easy to mail or carry.

The application design emphasizes personalization, with laser technology achieving fine textures and chemical polishing providing a mirror-like reflection to enhance visual appeal. The composite structure, combined with silk or leather, elevates the gift's quality. The wear-resistant properties of the tungsten alloy ensure the cards maintain their pristine appearance with repeated handling, resulting in high collectible value.

7.5.4 Tungsten Alloy Industry and Asset Management Signage

Tungsten alloy industrial and asset management signage is made by processing thin sheets of tungsten alloy into durable signs for permanent marking of equipment, tools, or assets. These signs resist wear, corrosion, and high temperatures in industrial environments through their high hardness and chemical stability, ensuring long-term legibility of information. After being rolled into thin plates, tungsten alloy sheets are laser-engraved or stamped with numbers, barcodes, or QR codes. Surface polishing or brushing

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enhances weather resistance. The chemical inertness of tungsten alloy prevents corrosion from acids, alkalis, or oils, making it suitable for outdoor or chemical environments.

In industrial signage applications, tungsten alloy signs are fixed to machinery, pipes, or containers, withstanding vibration and cleaning. Their high density provides a sense of stability, and they are securely attached with lanyards or rivets. Asset management signage is used on warehouse shelves or IT equipment, with QR codes linking to digital systems for tracking and inventory management. The wear resistance of tungsten alloy ensures the signs remain clear and the information remains legible even with frequent scanning or friction.

The application design prioritizes practicality, featuring smooth, scratch-resistant edges and precise holes for easy mounting. Thin yet robust, it resists bending and cracking, with a black chrome plating enhancing concealment and fingerprint resistance. Its chemical stability allows for high-pressure water jet cleaning or solvent wiping. The machinability of tungsten alloy nameplates allows for mass customization, and templated patterns reduce costs.

7.5.5 Tungsten alloy clothing and luxury goods tags

Tungsten alloy clothing and luxury brand hangtags are fashion tags made from thin tungsten alloy sheets, attached to clothing, bags, or jewelry. They give the products a metallic feel and a high-end positioning. These hangtags enhance brand image through their weight and luster, distinguishing them from traditional plastic or paper labels. The tungsten alloy sheets are precisely cut into brand logos or geometric shapes, with brushed, mirrored, or gold-plated surfaces. The chemical hardness of tungsten alloy ensures that the hangtags will not scratch or deform during wear and tear, maintaining their permanent shine.

In apparel hangtag applications, tungsten alloy tags are attached to garments via thin chains or ribbons, their weighty feel conveying luxury. Laser engraving of the brand name or limited edition number enhances exclusivity. Luxury handbag hangtags are often larger, with embossed textures adding a three-dimensional effect, and are plated with black titanium or rose gold to match the product's color scheme. Jewelry hangtags utilize corrosion-resistant tungsten alloys, ensuring long-term preservation alongside precious metal jewelry. The application design emphasizes both aesthetics and functionality, with rounded, polished edges and delicately crafted holes to prevent tearing and breakage. Finely adjusted thickness balances weight and softness, while chemical stability resists the corrosive effects of perfumes and sweat. The machinability of tungsten alloy tags allows for small-batch, high-end customization, with 3D textures or gemstone inlays enhancing their artistic value.

7.5.6 High-end Tungsten Alloy Business Cards and Social Etiquette Cards

Tungsten alloy business cards and social etiquette cards are made by processing thin tungsten alloy sheets into business card or gift card form for business communication or social occasions. These cards convey professionalism and taste through their metallic weight and exquisite craftsmanship, distinguishing them

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from ordinary paper business cards and enhancing the holder's personal image. Tungsten alloy sheets are rolled to standard business card thickness, and the surface is laser-engraved with the name, title, and contact information. The chemical hardness of tungsten alloy ensures that the card will not bend or wear down when rubbed against a wallet or business card holder, maintaining a permanent luster.

In high-end business card applications, tungsten alloy offers a cool, metallic feel that draws attention when taken out. The plating, such as gunmetal or silver-white, matches a professional style, while the brushed texture adds understated luxury. Social etiquette cards, used for wedding invitations, thank-you cards, or formal invitations, feature elegant lettering or designs, are thin yet substantial, and are easy to mail or deliver.

The application design pays attention to detail, with chamfered edges to prevent scratches, and QR codes linking to personal websites or digital business cards. Chemical stability resists sweat and alcohol smudges, ensuring clear and lasting information. The machinability of the tungsten alloy cards allows for double-sided engraving, one side for information and the other for artistic designs, enhancing their collectible value.



CTIA GROUP LTD Tungsten Alloy Sheets

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Chapter 8 Common Problems and Solutions for Tungsten Alloy Sheets

8.1 Fundamental Material Issues and Solutions of Tungsten Alloy Sheets

Tungsten alloy sheets mainly stem from deviations in composition distribution, crystal structure, and physical properties. These issues can affect the uniformity, reliability, and functionality of the material during production and application. Compositional inhomogeneity leads to localized performance differences, structural defects influence mechanical behavior, and deviations in physical properties may result in poor matching with downstream applications. Solutions emphasize process optimization and control, such as homogenization of mixing, heat treatment repair, and parameter adjustment. The causes of these problems are often related to powder characteristics, sintering kinetics, and processing stress, and can be effectively mitigated through systematic detection and feedback mechanisms.

Solving fundamental material problems emphasizes a combination of prevention and correction, with strict purity management in the raw material stage, refined parameters in the forming and sintering stage, and thermomechanical control in the post-processing stage. Chemical principles guide the solution, with diffusion promoting uniformity and restoration reducing defects. The flexibility of problem-solving allows for adjustments based on the alloy system; for nickel-iron systems, the focus is on strength balance, while for tungsten-copper systems, the emphasis is on thermal conductivity. Environmental factors can amplify problems, such as humidity-induced uneven oxidation, requiring controlled drying.

8.1.1 Issues related to composition and structure

Tungsten alloy sheets mainly manifest as uneven elemental distribution and crystal defects. These problems affect the two-phase equilibrium and interfacial bonding of the microstructure, thus impacting macroscopic properties. Inhomogeneous composition stems from insufficient powder mixing or sintering diffusion, while structural defects include dislocations, porosity, and segregated phases. Solutions focus on homogenization methods and restorative heat treatment, leveraging chemical diffusion and recrystallization mechanisms. Problem detection is achieved through spectral mapping and electron microscopy observation, allowing for early intervention to reduce waste.

Solving these problems also involves the coordinated operation of the entire process chain: optimizing the powder at the front end to reduce initial deviations, controlling diffusion during mid-stage sintering, and mitigating defects during final processing. The problems are more pronounced with high-tungsten alloys, where uniformity is difficult to maintain when the binder phase is low. Environmental control, such as atmosphere purity, also affects the severity of the problems.

8.1.1.1 Problems and Homogenization Methods of Inhomogeneous Tungsten Alloy Composition

Tungsten alloys mainly stems from insufficient powder mixing, inadequate sintering diffusion, or elemental segregation caused by excessively large billet size. This unevenness manifests as local enrichment of the binder phase or agglomeration of tungsten particles, affecting density distribution and

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mechanical equilibrium. The causes of the problem are evident in the mixing stage, where differences in powder particle size or electrostatic discharge lead to separation. During sintering, uneven liquid phase flow exacerbates segregation, and differences in the diffusion rates of chemically binding elements amplify the gradient.

The homogenization method first enhances powder mixing, employing high-energy ball milling or spray drying for pre-alloying to promote elemental micro-distribution. During sintering, extended holding time or segmented temperature control drives element migration through chemical diffusion, optimizing liquid phase flow for uniformity. Hot isostatic pressing post-treatment applies anisotropic pressure to accelerate closed-cell elimination and diffusion homogenization. Annealing further homogenizes the powder, and prolonged vacuum holding allows for solution treatment adjustments.

In application, large billets are combined with multi-zone heating furnaces to reduce temperature gradients, while small billets are stirred to enhance convection. Chemical detection, such as energy dispersive spectroscopy (EDS), verifies inhomogeneous regions and guides parameter iteration. Preventive measures include powder pretreatment to remove agglomerates and fine-tuning the proportions to balance flowability.

This problem is common in high-tungsten content alloys. Homogenization improves interfacial bonding and reduces performance deviations. Store the powder in a dry environment to prevent moisture absorption and separation. Variants such as mechanical alloying allow for thorough pre-homogenization.

8.1.1.2 Types of Crystal Structure Defects and Repair Strategies

Tungsten alloy sheets include dislocations, porosity, grain boundary segregation, and abnormal precipitates. These defects originate from processing stress and imperfect sintering, affecting strength, toughness, and thermal stability. Dislocation defects accumulate due to rolling hardening, porosity results from residual sintering and insufficient density, grain boundary segregation leads to impurity enrichment, and precipitates exhibit abnormal size or uneven distribution. Chemically, defects disrupt the lattice period and reduce the binding energy.

The repair strategy primarily employs heat treatment, including vacuum annealing to release dislocations, chemical diffusion annihilation or rearrangement, and a holding period to restore the slip system. Pore repair involves high-pressure closure via hot isostatic pressing, followed by densification after gas expulsion. Grain boundary segregation is addressed by purifying raw materials to reduce the source, followed by high-temperature homogenization and diffusion dilution. Abnormal precipitates are treated by rapid cooling and solidification to lock in homogeneity, or by aging to control size.

In application strategies, cold-rolled defects are often repaired in stages using intermediate annealing, while sintering defects are remedied by post-pressurization. Chemical vacuum atmospheres are used to prevent the introduction of new defects. Electron microscopy is used to observe defect types and guide strategy selection. Multi-directional forging is used to prevent directional dislocations.

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8.1.2 Problems with physical property deviations in tungsten alloy sheets

Tungsten alloy sheets mainly involve abnormal density and hardness, and mismatch between thermal conductivity and expansion. These deviations stem from process fluctuations and compositional differences, affecting application compatibility and reliability. Density deviations result from uneven sintering, abnormal hardness from insufficient work hardening or annealing, low thermal conductivity from liquid phase segregation, and expansion mismatch from an imbalanced binder phase ratio.

The solution focuses on parameter stability and post-adjustment, with density corrected through pressure compensation, hardness controlled by heat treatment, and thermal conductivity expansion ratio optimized. Problem detection involves multi-point measurement averaging to trace process steps.

8.1.2.1 Causes and Adjustment Techniques for Abnormal Density and Hardness

Tungsten alloy sheets are mainly caused by insufficient sintering or uneven deformation during processing. Low density results in residual porosity, while high hardness is due to accumulation during cold working or over-annealing. Chemically, this leads to interruption of the continuous phase in the porosity and hardening of dislocations pinning grain boundaries. The causes can be traced back to mixed segregation leading to local differences in the liquid phase and amplified deviations in the sintering temperature window.

Adjusting the technical density focuses on hot isostatic pressing to achieve density, while high-pressure closed-cell treatment improves uniformity. Abnormal hardness is addressed through annealing or aging strengthening, with chemical diffusion or precipitation equilibrium used for recovery. Low-density billets undergo secondary sintering, while high-hardness billets are subjected to intermediate annealing for grading.

In technical applications, multiple pressure repairs are used to address abnormal density in large billets, while fine adjustments are made to the rolling process for smaller pieces to improve hardness. Chemical analysis is employed to assess the degree of abnormality in weight loss or indentation. This process helps prevent issues related to powder uniformity and parameter stability.

8.1.2.2 Problems and Optimization Schemes Regarding the Mismatch Between Thermal Conductivity and Thermal Expansion

The mismatch between the thermal conductivity and thermal expansion of tungsten alloy sheets stems from an imbalance in the distribution or proportion of the binder phase. Low thermal conductivity indicates a discontinuous copper phase, while high expansion indicates excessive binder. Chemically, thermal conductivity depends on electron-phonon transport, which is determined by the volume of the expanded phase. The problem arises from uneven sintering flow or misproportioning.

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The optimized thermal conductivity is enhanced through copper infiltration or activated sintering to create continuous, uniform chemical flow channels. Expansion mismatch is addressed by adjusting the tungsten bond ratio, with molybdenum partial substitution fine-tuning the coefficient. Heat treatment homogenizes the distribution, and annealing facilitates diffusion at the interface.

In the application of this solution, the thermal conductivity of the tungsten-copper system is optimized after melting and infiltration, followed by rolling to straighten the channel. The expansion of the nickel-iron system is controlled by annealing for release. The matching degree of the thermal conductivity meter and dilatometer is verified through optimized testing.

8.2 Problems and Solutions in the Production and Manufacturing of Tungsten Alloy Sheets

Tungsten alloy sheets primarily focus on optimizing the entire supply chain from raw materials to finished products. These challenges include deviations in powder metallurgy processes, instability in rolling forming, and challenges in quality inspection and control. Solutions are achieved through process parameter adjustments, equipment improvements, and quality feedback mechanisms. Manufacturing problems often stem from material properties such as tungsten's high melting point and the diffusion behavior of alloying elements, leading to uneven microstructure or performance fluctuations. Solutions emphasize a combination of prevention and correction: purification control in the powder stage reduces initial defects; pass design in the rolling stage alleviates stress accumulation; and multiple methods are used in combination in the inspection stage to improve accuracy. Solving manufacturing problems also involves systems engineering, process chain linkage, remediation of front-end problems at the back end, and feedback from the back end to improve the front end. The high density of tungsten alloy sheets amplifies problems such as cracks or deviations in thin-sheet production, requiring meticulous management. Environmental factors such as temperature and humidity affect manufacturing stability and need constant control.

8.2.1 Problems with Powder Metallurgy Processes

Problems in powder metallurgy processes mainly manifest as defects in powder preparation and malfunctions in the sintering process. These issues affect the quality of the billet and the final sheet microstructure, and can be resolved by identifying the causes and improving the process. Defects in powder preparation stem from uneven reduction or the introduction of impurities, while sintering malfunctions are related to temperature control and atmosphere management. Problem diagnosis requires a combination of chemical analysis and microscopic observation, and improvement strategies include parameter optimization and auxiliary technologies.

Solving process problems focuses on fundamental steps: powder purification reduces defect sources, and sintering homogenization improves density. The refractory nature of tungsten alloys exacerbates problems at high temperatures, requiring precise control. Environmental cleanliness control prevents external contamination.

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8.2.1.1 Identification and Control Measures for Defects in Powder Preparation

The identification and control measures for defects in powder preparation mainly target the purity, particle size, and morphology of tungsten powder and alloy element powders. These defects, such as agglomeration, impurity enrichment, or wide particle size distribution, may lead to uneven mixing and sintering porosity. Defect identification is achieved by detecting the distribution using a laser particle size analyzer, observing the morphology using a scanning electron microscope, and analyzing impurities using spectral analysis. Chemically, impurities such as oxygen or carbon remain during reduction, while particle size unevenness originates from temperature fluctuations.

The defects were identified during the hydrogen reduction of tungsten oxide. Insufficient water vapor removal at low temperatures led to oxygen residue, which then grew abnormally at high temperatures, forming coarse powder. Gas entrainment during alloy powder atomization caused pores. After identification and classification, morphological defects were clearly observed as agglomerated particles under electron microscopy, and impurity spectral peaks were prominent.

The control measures first optimize reduction parameters, using staged temperature control to refine particle size, adjusting hydrogen flow to regulate water vapor concentration, and employing chemical reducing agents to assist in reducing oxygen levels. Sieving and airflow classification remove abnormal particles, while ball milling activates and breaks up agglomerates. A pretreatment hydrogen deoxygenation furnace purifies the gas, reducing source impurities. Powder storage involves drying, inert gas sealing, and prevention of oxidation and agglomeration.

In this application, high-purity tungsten powder is used to control the multi-stage recrystallization of ammonium tungstate precursors, while alloy powder is prepared using a carbonyl method to achieve fine purity. Iterative parameters are monitored and feedback is applied to ensure uniform mixing after narrowing the particle size distribution. Chemical cleaning and acid washing remove surface impurities, followed by drying and sieving.

8.2.1.2 Diagnosis of Sintering Process Faults and Process Improvement

The diagnosis and process improvement of sintering process faults mainly target problems such as under-sintering porosity, over-sintering coarsening, and deformation segregation. These faults affect the density and uniformity of the billet structure. Diagnosis is achieved through temperature recording, density measurement, and metallographic observation. The causes of the faults are reflected in the temperature window deviation, insufficient liquid phase rearrangement in under-sintering, excessive liquid phase in over-sintering leading to particle growth, and high atmospheric moisture leading to oxidation inclusions.

Diagnostic methods include analyzing furnace temperature profiles for deviations, observing porosity distribution in metallographic sections, and testing for segregation using density gradients. Chemical analysis of volatile residues confirms impurities and malfunctions.

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Process improvements begin with adjusting the temperature window, optimizing the liquidus period through segmented heating and holding, and using chemical additives to extend the window. Atmosphere improvements include dew point control and enhanced flow, reducing oxidation by removing water vapor. Hot isostatic pressing addresses sintering defects, and high-pressure closed-cell construction improves densification. Furnace loading improvements include vertical suspension or sand bed support to reduce deformation. In applications, high-density alloy sintering is improved through integrated hot pressing, with parameter fine-tuning after diagnostics. Increased chemical purity and pre-degassing reduce gas defects. Variants such as vacuum sintering replace hydrogen to address water vapor issues.

8.2.2 Rolling and Forming Issues

Rolling and forming problems mainly include hot-rolling cracks and unstable cold-working deformation. These problems affect the integrity and thickness uniformity of the sheet material, and can be solved through causal analysis and control methods. Hot-rolling cracks originate from stress concentration, while cold deformation causes hardening accumulation. Diagnosis involves observing the surface and cross-section, improving pass design, and annealing. Problem solving focuses on deformation coordination, preventing lateral pressure during hot rolling, and releasing stress during cold working annealing. The high hardness of tungsten alloys makes the problem more prominent in thin sheet rolling. Environmental temperature control affects deformation.

8.2.2.1 Causes and Prevention Methods of Hot Rolling Cracks

The main causes of hot-rolled crack formation are high-temperature stress concentration and uneven microstructure. Cracks initiate and propagate from the edge or surface. Chemically, the stress is high at weak interfaces, exacerbating the brittleness of tungsten particles. The causes can be traced back to the porosity or segregation of the billet, and when the rolling reduction is large, the stress exceeds the toughness.

Prevention methods first optimize billet sintering to achieve density and reduce initial defects. The rolling process involves gradual reduction, with initial small reductions for initial shaping and fine-tuning later. Chemical lubrication and high-temperature coatings reduce frictional stress. Side guide rolls constrain the sheet shape and prevent edge tensile stress. Intermediate heating ensures uniform temperature and restores plasticity. In application, high-density alloys are used for preventative cladding rolling to isolate air and buffer stress. Crack morphology is diagnosed and observed; surface cracks are addressed by adjusting lubrication, and internal cracks by improving billet quality. Variations include warm rolling replacing some hot rolling processes.

8.2.2.2 Analysis and Control of Cold Working Deformation

The analysis and control of cold working deformation mainly target hardening accumulation and warping, which affect thickness accuracy and surface quality. The analysis is achieved through stress curves and

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metallographic observation. The causes are manifested in dislocation multiplication; chemically, the binder phase has limited plasticity, and tungsten particles impede deformation, leading to localized strain.

Deformation control methods include small and frequent pass reductions, intermediate annealing to release hardening, and chemical diffusion to restore slip. Uniform lubricant application reduces frictional deformation. Tension control stabilizes sheet shape and prevents mid-waves and edge waves. Adjustments to the rolling process are made after analysis; annealing is increased when hardening is high. In application control, thin sheet deformation is controlled by cross-rolling to ensure uniform stress distribution. High chemical purity reduces impurities and pinning dislocations. Variations include warm and cold bonding.

8.2.3 Quality Inspection and Control Issues

Quality inspection and control issues mainly include challenges in non-destructive testing (NDT) and dimensional tolerance deviations. These problems affect the accuracy of finished product acceptance and application. Solutions are achieved through alternative methods and technological improvements. NDT challenges include matrix interference and dimensional deviations due to processing fluctuations. Control focuses on online monitoring and feedback adjustments. Problem-solving emphasizes the combined use of multiple methods, replacing destructive sampling with NDT solutions, and using precision equipment to correct dimensional deviations. The high density of tungsten alloys makes testing in thin sheets challenging. Environmental calibration also affects accuracy.

8.2.3.1 Challenges and Alternative Solutions in the Application of Nondestructive Testing Technology

The main challenges in applying nondestructive testing (NDT) techniques lie in the high density of tungsten hindering X-ray penetration and the attenuation of ultrasonic waves. These challenges make it difficult to identify internal defects such as pores or cracks, and chemical density gradients interfere with the signal. These problems are more pronounced in thick sections, while thin sections experience greater surface interference.

The alternative solution combines X-ray computed tomography (CT) to adjust energy penetration, and high chemical purity to reduce background noise. Ultrasonic phased array technology optimizes beam focusing, replacing traditional probes. Eddy current detection is used to detect surface cracks, and magnetic powder assists in the detection of magnetic alloys. The solution combines X-ray internal examination with ultrasonic compensation.

8.2.3.2 Handling of Dimensional Tolerance Deviations and Accuracy Improvement

The handling and precision improvement of dimensional tolerance deviations mainly target thickness, width or flatness deviations caused by rolling fluctuations and thermal effects. These deviations are

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caused by unstable rolling pressure and uneven stress release in each pass, as well as amplified differences in thermal expansion in chemical terms.

The processing methods include online measurement and feedback to adjust the roll gap, and automatic compensation by the precision rolling mill. Hot leveling corrects warpage, and chemical annealing releases residual stress. Precision is improved through a high-rigidity roll system and tension control to reduce elastic deformation.

In applications where thin sheet deviations are adjusted in real-time using laser measurement, thick sheet forging allows for grinding to compensate for pre-existing tolerances. High chemical purity reduces thermal effect deviations. Variants include CNC rolling.

8.3 Application, Performance Issues, and Solutions of Tungsten Alloy Sheets

tungsten alloy sheets mainly revolve around their practical performance in various fields. These issues include high-temperature fatigue, vibration and shock, shielding efficiency, biocompatibility, electrical conductivity and magnetism, and corrosion and oxidation. Solutions are achieved through mechanism analysis, design optimization, and material modification. Application problems often stem from the mismatch between environmental conditions and material properties. Fatigue failure is common in high-temperature environments, radiation shielding efficiency degradation needs to be considered, and abnormal electrical conductivity in electronic medical devices can affect functionality. Solving performance problems emphasizes prevention and correction, mechanism investigation to guide design, and modification techniques to improve adaptability.

The systematic nature of problem-solving is reflected in multi-scale interventions, ranging from microstructural adjustments to macroscopic protective coatings. Aerospace applications emphasize fatigue resistance and shock resistance, radiation shielding focuses on efficiency recovery and safety improvements, while electronic and medical applications prioritize conductivity stability and corrosion resistance. The biphasic structure of tungsten alloy sheets plays a role in this solution, with tungsten particles providing rigid support and the binder phase modulating toughness. Environmental factors such as temperature cycling or medium exposure amplification require targeted solutions.

8.3.1 Application Issues of Tungsten Alloy Sheets in Aerospace

Tungsten alloy sheets in aerospace involve fatigue and vibration/shock loads under high-temperature environments. These issues affect the long-term stability and structural integrity of the materials, and are mitigated through strengthening treatments and impact-resistant design. Aerospace components are subjected to repeated thermal stresses and mechanical loads, and tungsten alloy sheets, used as counterweights or thermal management materials, must address these challenges. Problem analysis emphasizes mechanism identification and design optimization; high-temperature fatigue stems from the accumulation of microscopic damage, while vibration/shock is related to stress wave propagation.

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Solving application problems also involves material selection and process improvement. Tungsten alloys offer a balance in density and modulus for aerospace applications, but the harsh environments necessitate tailored solutions. Tungsten -nickel-iron systems are common in aerospace components, with the binder phase coordinating deformation. Environmental simulation testing guides solutions, and accelerated fatigue testing assesses lifespan.

8.3.1.1 Mechanism and Strengthening Treatment of High-Temperature Fatigue Failure

The mechanism of high-temperature fatigue failure mainly stems from the evolution of microscopic damage under repeated thermomechanical loading. In tungsten alloy sheets, this mechanism manifests as grain boundary slip, dislocation climb, and microcrack initiation and propagation. Chemically, elemental segregation at the interface reduces bonding strength, and stress concentration around tungsten particles induces damage. The process is phased: initially, dislocations multiply to form persistent bands; in the middle stage, micropores coalesce; and in the later stage, cracks propagate rapidly until fracture. Thermal cycling exacerbates the mechanism, with uneven expansion generating thermal stress, and oxide layer formation further weakening the surface.

Strengthening treatments first involve alloy design, doping with rare earth elements or carbides to disperse and pin grain boundaries, and chemically controlling the segregating elements to reduce slip rate and raise the fatigue threshold. Heat treatment, solution treatment, and aging precipitate fine phases, strengthening the toughness of the binder phase, while controlling the treatment temperature window to avoid coarsening. Surface strengthening, such as ion implantation of nitrogen or carbon, forms a gradient layer, and chemical diffusion enhances surface hardness and buffers crack propagation.

In processing applications, multi-pass annealing restores the microstructure, and chemical purity management reduces impurity-induced damage. Mechanism verification involves fatigue testing to simulate cycles and observe fracture characteristics for adjustments. Variations such as surface rolling introduce compressive stress to counteract tensile fatigue.

8.3.1.2 Problems with Vibration and Shock Loads and Shock-Resistant Design

The main problem with vibration and impact loading lies in the localized damage caused by stress wave propagation. In tungsten alloy sheets, this manifests as microcrack initiation and propagation, stress concentration at chemically weak interfaces, and amplification of the impact effect due to the brittleness of tungsten particles. The cause is the superposition of vibration frequency resonance and high instantaneous impact load, coupled with insufficient material damping to absorb energy, leading to accelerated fatigue.

The impact-resistant design first optimizes the composite structure, laminating tungsten alloy sheets with polymers, and using chemical binders to buffer shock waves. Texture control is incorporated into the design, with oriented fibers enhancing directional strength. Surface coatings, such as elastic polymers, absorb energy, while chemical compatibility ensures stable adhesion.

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In design applications, simulated vibration tests assess the problem and adjust the thickness distribution to disperse stress. Mechanism analysis and finite element modeling predict damage points, guiding thickening or reinforcement. Variants such as gradient density design provide gradual absorption. In summary, the problems of vibration and impact loads and impact-resistant design embody dynamic response engineering strategies. Through buffer optimization, the vibration resistance of tungsten alloy sheets is improved, supporting stability in aerospace applications. Through design improvements, impact damage is gradually mitigated, promoting the reliability of materials in vibration environments.

8.3.2 Issues related to the application of tungsten alloy sheets in radiation shielding

Tungsten alloy sheets in radiation shielding involve efficiency degradation and biocompatibility concerns. These problems affect shielding effectiveness and safe use, and can be resolved through efficiency recovery and safety improvements. In radiation shielding applications, tungsten alloy sheets, used as collimators or protective layers, must withstand long-term radiation exposure. Efficiency degradation stems from structural changes, while biocompatibility concerns are related to surface reactions.

Solving application problems emphasizes material stability and optimized protection. Tungsten's high density provides a thickness advantage in shielding, but specific solutions are needed for different radiation environments. Tungsten -nickel-copper systems are common in shielding, and their non-magnetic nature supports medical compatibility. Environmental simulation testing guides solutions, and radiation dose testing assesses changes.

8.3.2.1 Reasons for shielding efficiency attenuation and efficiency recovery

The main reason for the decline in shielding efficiency lies in radiation-induced structural changes, such as swelling, porosity formation, and phase transitions. In tungsten alloy sheets, these manifest as a decrease in density and fluctuations in the attenuation coefficient. Chemically, radiation-displaced atoms generate vacancy clusters, and interface damage amplifies scattering. The causes and processes are dose-dependent, with low doses resulting in microscopic defects and medium- to high-dose macroscopic deformations.

Efficiency recovery is achieved first through heat treatment to repair defects, chemical diffusion to heal vacancies, and controlled annealing temperature to prevent secondary phase precipitation. A protective surface coating blocks incident radiation, and a chemically inert layer absorbs energy. Stabilizers are added during the recovery process to pin defects and reduce swelling.

8.3.2.2 Assessment of Biocompatibility Hazards and Safety Improvement

The assessment and safety improvements for biocompatibility hazards primarily target surface release and tissue reactions. In tungsten alloy sheets, these hazards manifest as limited dissolution of binder elements, and chemically, nickel or copper ions may induce allergies. Assessment is conducted through

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leaching tests and cell compatibility tests. The causes of these hazards include surface oxidation or abrasion exposing the active phase.

Safety improvements begin with surface passivation to form a stable oxide film, followed by chemical anodizing or plating to block ion migration. Evaluation criteria include biological testing of cell adhesion and proliferation rates, and formulation improvements to reduce the proportion of active elements.

8.3.3 Application Issues of Tungsten Alloy Sheets in Electronic and Medical Devices

Tungsten alloy sheets in electronic and medical devices involve abnormal electrical conductivity and magnetism, as well as corrosion and oxidation. These issues affect conductivity stability and device lifespan, and can be resolved through troubleshooting, modification, and protective coatings. In electronic medical applications, tungsten alloy sheets, used as heat sinks or shielding, need to address conductivity fluctuations and oxidation. Abnormalities originate from impurities or surface changes, while corrosion is related to media erosion.

Solving application problems emphasizes troubleshooting mechanisms and coating optimization. Tungsten-copper systems are common in electronics, exhibiting good thermal and electrical conductivity. Environmental testing guides solutions, and corrosion testing accelerates the assessment of changes. In summary, this application problem-solving demonstrates the material stability of electrochemical processes, supports the reliable performance of tungsten alloy sheets in devices through modification schemes, and promotes technological advancements in the field of electronic medical devices.

8.3.3.1 Investigation of Electrical Conductivity and Magnetic Anomalies and Material Modification

The causes of electrical conductivity and magnetic anomalies mainly lie in the introduction of impurities and fluctuations in phase composition. In tungsten alloy sheets, these factors manifest as interruption of conductive channels or accidental magnetization. Chemically, oxygen impurities form an insulating layer, and iron element segregation generates magnetic domains. Anomaly investigation is conducted through resistance measurements and hysteresis curves to locate impurities or segregation regions.

Material modification begins with purifying the raw materials to reduce oxygen and iron through chemical reduction pretreatment. The modified alloy is then modified by adjusting the copper ratio to enhance conductivity, and molybdenum doping weakens magnetism. Surface cleaning restores conductivity, and chemical polishing removes oxidation.

8.3.3.2 Protection and Coating Technology for Corrosion and Oxidation Problems

Protection and coating technologies for corrosion and oxidation mainly target media erosion and air oxidation. These problems manifest as surface pitting and performance degradation in tungsten alloy

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sheets, where the binder phase preferentially reacts to form a porous layer. The causes are humid environments or high-temperature oxygen exposure.

The protective coating technology first involves electroless nickel- phosphorus plating to form a dense film, followed by a chemical autocatalytic reaction for uniform coverage. The coating process then involves vacuum plating with chromium-nitrogen or DLC to enhance hardness and inertness. The protective pretreatment passivates the surface, and the oxide film stabilizes the substrate.



CTIA GROUP LTD Tungsten Alloy Sheets

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appendix

Appendix A: Chinese Tungsten Alloy Sheet Standard

Chinese [tungsten alloy sheet](http://www.chinatungsten.com) standards is primarily the responsibility of the National Technical Committee on Standardization of Nonferrous Metals (TC243) and its subcommittees, covering aspects such as the chemical composition, physical properties, processing technology, and quality control of tungsten alloys. These standards are based on national industrial policies and mineral resource planning, ensuring the reliability and consistency of tungsten alloy sheets in industrial applications. The standards emphasize the use of high-purity tungsten powder, the standardization of liquid-phase sintering processes, and strict limitations on impurities such as oxygen, carbon, and phosphorus to avoid structural defects and performance deviations. The standard system includes national standards (GB/T series), industry standards (YS/T series), and enterprise standards, applicable to common systems such as tungsten - nickel-iron, tungsten-nickel-copper , and tungsten-copper .

Standards typically specify composition ranges, density distributions, hardness indices, and dimensional tolerances. After sintering, the billet must undergo thermomechanical processing to verify uniformity. Chemical analysis methods are standardized, such as the cinquerin gravimetric method for determining tungsten content, ensuring accuracy. Standards also address environmental and safety requirements, emphasizing the legality and sustainability of raw material procurement and preventing the use of illegal mineral products. In recent years, with the strengthening of entry requirements in the tungsten industry, standards have incorporated export control elements, providing compliance guidance for the processing and trade of specific tungsten alloy products . The implementation of tungsten alloy sheet standards promotes standardization throughout the entire process from powder metallurgy to finished sheets, supporting the expansion of applications in high-end manufacturing.

National Standards (GB/T Series)

National standards (GB/T series) are the core specifications for tungsten alloy sheets in China, issued by the State Administration for Market Regulation and the Standardization Administration of China. They cover the general requirements, test methods, and performance indicators of tungsten alloys. These standards apply to the chemical composition analysis, machining, and quality acceptance of tungsten alloy sheets, ensuring a balance in density, hardness, and thermal stability. The national standards for tungsten alloy sheets emphasize the standardization of powder metallurgy processes, from the purity of tungsten powder to the control of the sintering temperature window. Chemically, they specify the tungsten content ratio, binder phase ratio, and impurity thresholds to achieve a uniform distribution of the two-phase microstructure.

The standard-setting process involved multi-party collaboration, including nonferrous metal research institutes and manufacturing enterprises, referencing international standards but incorporating China's resource characteristics. The GB/T standard for tungsten alloy sheets includes general specifications for tungsten bars, plates, and alloy plates, specifying surface finish, thickness tolerances, and annealing

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conditions. Chemical testing methods, such as the determination of tungsten trioxide content, utilize the ammonium tungstate gravimetric method to ensure accuracy. The standard also covers heat treatment requirements, optimizing the recrystallization temperature in the annealing process to prevent grain coarsening from affecting mechanical properties. Export-oriented standards incorporate regulatory clauses, specifying reporting requirements for tungsten-nickel-iron or tungsten-nickel-copper alloy specifications to support international trade compliance .

At the application level, the GB/T standard guides the use of tungsten alloy sheets in precision instruments and thermal management, covering a wide range of sizes from micron-sized foils to centimeter-sized plates . The standard revision cycle takes into account technological advancements, such as the inclusion of nano-reinforced alloys. During implementation, companies must undergo verification by certified laboratories, with batch sampling for composition and density testing. Environmental sustainability is incorporated into the standard, encouraging the recycling of tungsten powder to reduce resource consumption.

Industry Standards (YS/T Series)

Industry standards (YS/T series), overseen by the Ministry of Industry and Information Technology, are formulated for the chemical analysis and processing of tungsten alloy sheets, providing more detailed technical specifications. These standards are applicable to the production of tungsten-copper alloys and tungsten-based high- density alloy sheets, ensuring accurate determination of chemical composition and consistent performance. YS/T standards focus on methods for determining tungsten content, such as the cinquercetin gravimetric method, which achieves high-precision analysis through dissolution and precipitation separation, suitable for verifying the tungsten percentage in tungsten-copper alloys. The standards also specify sample preparation, instrument calibration, and error control, chemically emphasizing the subtraction of matrix interferences.

the tungsten alloy sheet industry standard includes details of the powder metallurgy process, from powder mixing to temperature profiles for liquid phase sintering, and optimization of the liquid phase amount to promote particle rearrangement. The YS/T series standards cover sheet specifications for tungsten - nickel-iron and tungsten-nickel-copper systems, specifying hardness distribution and surface roughness requirements, and supporting processing adaptability for mold and shielding applications. The standards are developed with reference to national planning, incorporating resource access conditions to ensure the legality of raw materials and environmental compliance .

In applications, the YS/T standard guides the standardization of quality control, dimensional tolerance, and thermal conductivity testing methods for tungsten alloy sheets in the electronics and medical fields. The revision process incorporated user feedback and included clauses for emerging alloys such as tungsten-molybdenum composites. Implementation requires companies to establish internal laboratories and regularly calibrate testing equipment. Regarding environmental management, the standard encourages low-energy sintering technologies to reduce carbon emissions.

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Enterprise and local standards

Enterprise and local standards are supplementary regulations in the production of tungsten alloy sheets in China. Developed by non-ferrous metal enterprises or local industry associations, they provide flexible guidance for specific alloy systems or application scenarios. These standards are based on the national framework but incorporate enterprise process experience to ensure adaptability for mass production. Enterprise standards, such as the internal specifications of Zhuzhou Cemented Carbide Group, stipulate the rolling passes and annealing regimes for tungsten alloy sheets, and chemically optimize the distribution of the binder phase to improve toughness. Local standards are common in tungsten - producing areas such as Hunan and Jiangxi provinces, and, in conjunction with mineral resource planning, emphasize raw material traceability and impurity control.

These standards cover chemical analysis methods for tungsten-copper alloys , extending to trace element determination, and are applicable to compliance verification of exported products . Enterprise standards emphasize quality management systems, integrating ISO 9001 certification into production processes, and batch tracking to ensure consistency. Local standards promote regional collaboration, such as standardized specifications for tungsten-based high -density alloys, supporting supply chain optimization.

At the application level, enterprise standards guide the customization of tungsten alloy sheets in precision instruments, while local standards promote environmentally friendly production. Revisions dynamically respond to the market and incorporate high-entropy alloy clauses. During implementation, internal audits verify compliance with standards. Environmental sustainability emphasizes recycling and reducing waste powder emissions.

Appendix B International Standards for Tungsten Alloy Sheets

International standards for tungsten alloy sheets are primarily developed by organizations such as ASTM International and SAE International. These standards provide a globally unified regulatory framework covering the chemical composition, mechanical properties, and testing methods of heavy tungsten alloy sheets, ensuring interoperability of materials in aerospace, medical, and electronics fields. International standards emphasize the classification of high-density tungsten-based alloys , such as the grading system in ASTM B777, which defines specifications based on tungsten content and binder phase type. The standard development process involves collaboration among experts from multiple countries and references general requirements for powder metallurgy processes.

The international standard's chemical analysis section standardizes tungsten content determination and impurity limits, supporting certification for global trade. Performance indicators, including density distribution, hardness, and thermal conductivity, are applicable to sheet rolling and heat treatment verification. The standard also incorporates quality management systems, such as ISO 9001, to ensure production consistency. Export control standards, such as the Wassenaar Arrangement, influence the international circulation of tungsten alloys, emphasizing compliance reporting .

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In applications, international standards guide the use of tungsten alloy sheets in radiation shielding and heat sinks, with dimensional tolerances and surface roughness requirements supporting precision machining. Revision cycles consider technological advancements and incorporate clauses on composite alloys. Implementation requires third-party laboratory certification and batch testing compliance. Environmental sustainability encourages recycling practices.

ASTM International Standard

ASTM international standards are the core specifications for the export of tungsten alloy sheets from China. Developed by the American Society for Testing and Materials, they cover standard specifications for tungsten heavy alloy sheets, such as ASTM B777's classification of tungsten -nickel-iron and tungsten-nickel-copper alloys, defining density grades and mechanical requirements. These standards are applicable to the production and testing of sheets, chemically specifying tungsten content ranges, binder phase ratios, and impurity thresholds to ensure the balance of the two-phase microstructure.

ASTM B777 specifies in detail the chemical composition and physical properties of tungsten alloy sheets. After sintering, the sheets must be hot-rolled to verify uniformity. The standard includes test methods, such as the Cincinnatiel gravimetric method for determining tungsten content, and supports precision control. ASTM B760, which originally specified pure tungsten sheets and foils, extends to the rolling process specifications for alloy sheets.

In applications, ASTM standards guide the use of tungsten alloy sheets in aerospace and medical shielding, with dimensional tolerances and hardness specifications supporting processing adaptability. The revision process incorporated global feedback and included radiation tolerance provisions. During implementation, company-certified laboratories validate and batch sampling confirms compliance. Environmental management emphasizes sustainable production.

SAE International Standard

SAE international standards, developed by the Society of Automotive Engineers (SAE), address the application of tungsten alloy sheets in the aerospace field. Standards such as AMS 7725 specify performance requirements for heavy tungsten alloy sheets. These standards emphasize high strength and thermal stability, making them suitable for high-temperature components. SAE standards specify the chemical composition and microstructure of tungsten -nickel-iron alloys, chemically limiting ferromagnetism to avoid electromagnetic interference.

The AMS 7725 standard specifies in detail the density distribution and annealing state of tungsten alloy sheets. After sintering, the sheets must undergo forging and rolling to verify toughness. The standard includes test methods, such as tensile strength and fracture toughness determinations, and supports mechanical equilibrium.

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In applications, SAE standards guide the use of tungsten alloy sheets in flight hardware, with vibration tolerance and fatigue indicators supporting design. Revision cycles consider aerospace advancements and incorporate composite structure provisions. Implementation requires AS9100 certification and batch testing compliance. Environmental sustainability encourages low-energy processes.

ISO international standard

ISO international standards provide a globally unified framework for tungsten alloy sheets. Developed by the International Organization for Standardization, standards such as the integration of the ISO 9001 quality management system have been extended to general specifications for tungsten heavy alloy plates. These standards apply to the powder metallurgy production of sheets, chemically specifying purity and impurity control to ensure compliance with international trade regulations .

ISO standards specify the chemical analysis and physical testing of tungsten alloy plates, and the sintering process must meet environmental requirements. The standards include global certification guidelines and support export verification.

In applications, ISO standards guide the use of tungsten alloy sheets in electronics and medical fields, supporting functional requirements such as dimensional accuracy and corrosion resistance. The revision process involves multinational collaboration and incorporates sustainability provisions. During implementation, companies undergo audits, ensuring batch traceability and compliance. Environmental management emphasizes resource recycling. In summary, ISO international standards embody global quality assurance for tungsten alloy sheets, standardize production through management systems , and support the deepening of international cooperation.

Appendix C: Standards for Tungsten Alloy Sheets in Europe, America, Japan, South Korea, and Other Countries

sheet standard systems in countries such as the US, Europe, Japan, and South Korea are diverse. The US primarily uses ASTM standards, Europe references EN standards, Japan uses JIS standards, and South Korea uses KS standards. These standards cover the composition, properties, and processing of tungsten heavy alloy sheets, emphasizing regional industry needs. European and American standards focus on aerospace and medical applications, Japanese standards on fine chemicals, and South Korean standards supporting electronics exports. Standard development involves industry associations, referencing international standards while incorporating local resources.

These countries' standard chemistry specifies limits for tungsten content and impurities, and performance indicators include density and thermal conductivity. Applications support the use of tungsten alloy sheets in shielding and heat sinks. Dynamic response technology is being revised to incorporate alloy innovations. Implementation requires certified laboratories and batch verification compliance. Environmental sustainability emphasizes recycling.

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American standards (ASTM, AMS series)

global benchmarks for tungsten alloy sheets, developed by ASTM International and SAE. For example, ASTM B 777 classifies tungsten heavy alloy sheets, defining density grades and mechanical specifications. These standards apply to the powder metallurgy and rolling of sheets, chemically specifying the binder phase ratio of tungsten -nickel-iron alloys to ensure non-magnetic variants.

ASTM B777 specifies the chemical composition and test methods in detail, requiring heat treatment verification of sintered sheets. AMS 7725, for aerospace tungsten alloy sheets, emphasizes fatigue strength. Applications support the use of tungsten alloy sheets in aerospace and medical fields. The revision process underwent expert review and incorporated radiation provisions. AS9100 certification is implemented.

European Standards (EN Series)

European standards (EN series) are developed by the European Committee for Standardization. For example, EN 2685 provides general requirements for tungsten alloy sheets. These standards apply to the composition and properties of heavy tungsten alloys, chemically limiting impurities to ensure environmental compliance. EN standards specify sintering processes and dimensional tolerances, supporting the European trade of sheet materials. In applications, they guide the use of tungsten alloy sheets in nuclear and electronic applications. Revisions involve multinational collaboration. CE marking is enforced.

Japanese Standards (JIS series)

Japanese standards (JIS series) are formulated by the Japanese Industrial Standards Committee. For example, JIS H 7804 specifies the composition of tungsten alloy sheets. These standards are applied to electronic applications, focusing on fine chemical composition. JIS standards emphasize purity and processing precision, supporting the Japanese industry of tungsten alloy sheets. In applications, they guide the use of tungsten alloy sheets in semiconductors. They also revise technical guidelines and enforce JIS certification.

Korean Standard (KS Series)

Korean standards (KS series) are formulated by the Korean Agency for Industrial Standards. For example, KS D 3615 specifies the requirements for tungsten alloy sheets. These standards support electronic exports and chemically define thermal conductivity. KS standards specify testing methods to support the manufacture of sheets in Korea. In applications, they guide the use of new energy sources. They also revise industry collaborations and implement the KS mark.

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Appendix D Terminology Table for Tungsten Alloy Sheets

| Chinese terminology | Brief explanation |
|--------------------------------------|--|
| Tungsten alloy sheet | Thin plate-shaped materials made of tungsten as the main component and prepared and rolled using powder metallurgy. |
| High specific gravity tungsten alloy | High-density tungsten-based alloys , typically with a tungsten content of over 90%, are used for counterweights or shielding. |
| Liquid phase sintering | The sintering process involves the appearance of a liquid phase, which promotes particle rearrangement and densification. |
| binder phase | tungsten particles in the alloy provide plasticity and toughness. |
| Dissolution-reprecipitation | The mechanism by which tungsten atoms dissolve and re-precipitate in the binder phase during liquid-phase sintering promotes particle spheroidization. |
| Cold isostatic pressing | A method for uniformly pressing and molding powder blanks using a liquid medium. |
| Hot isostatic pressing | Post-processing technology that eliminates porosity and increases density under high temperature and high pressure. |
| Multi-leaf collimator | A beam shaping device composed of tungsten alloy blades in a radiotherapy equipment. |
| heat sink | Thermally conductive substrates used for heat dissipation of electronic devices are often made of tungsten-copper alloy . |
| pseudo-alloys | two non-solid substances , such as tungsten-copper alloys , are prepared by melt infiltration. |
| recrystallization annealing | High-temperature annealing induces recrystallization, eliminating processing stress and restoring plasticity. |
| work hardening | Cold working increases dislocation density, thereby improving hardness and strength. |
| Texture | The preferential distribution of crystal orientation caused by rolling deformation affects anisotropy. |
| passivation film | A protective oxide layer, formed spontaneously or artificially on the surface, enhances corrosion resistance. |
| Fisher grain size | Average particle size of powder determined by air permeation method. |
| Archimedes | The method of determining the density of materials by water displacement. |
| Vickers hardness | The hardness index measured by diamond indenter is applicable to tungsten alloys. |
| X-ray attenuation | The ability of a material to absorb and scatter X-rays or gamma rays. |
| coefficient of thermal expansion | The dimensional expansion rate of a material under temperature changes is important for matching with the substrate. |
| Biocompatibility | The material is safe when in contact with biological tissues; it is non-toxic and non-allergenic. |

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