Tungsten Alloy Weight Encyclopedia

中钨智造科技有限公司

CTIA GROUP LTD

CTIA GROUP LTD

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

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INTRODUCTION TO CTIA GROUP

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

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

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

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

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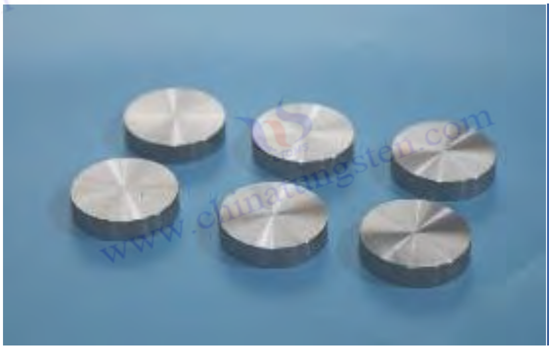
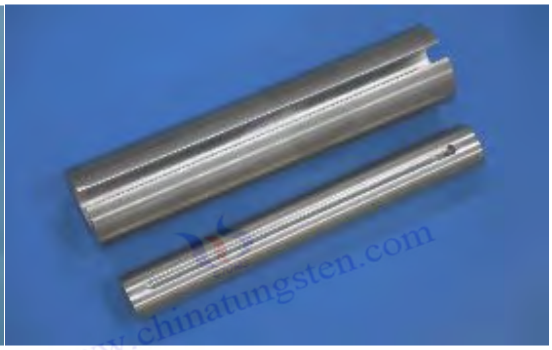

Table of Contents

Preface

Writing background and significance

With the rapid development of high-end industries such as aerospace, precision manufacturing, intelligent equipment, medical imaging and new energy vehicles, the counterweight system, as an important component to achieve mechanical balance, improve stability and precise functional control, is being given more and more technical and structural requirements. Although traditional counterweight materials such as lead, steel, copper, etc. have certain density advantages and processing feasibility, they can no longer meet the comprehensive requirements of the new generation of equipment for "high density, small size and high stability" in terms of performance, environmental protection and compact structure.

Tungsten alloy, especially high- density tungsten-based composite materials represented by W-Ni-Fe and W-Ni-Cu systems , has become an ideal material for modern high-performance counterweight systems due to its **ultra-high density (>17 g/cm³), excellent mechanical properties, outstanding environmental adaptability and non-toxic and environmentally friendly characteristics** . In aerospace, it is used to adjust the center of gravity and attitude control of aircraft; in the automotive industry, it serves the chassis balance and dynamic adjustment; in medical equipment, it ensures image stability and mechanical precision; in the civilian field, it is gradually replacing traditional heavy metal materials and entering high-end life equipment and precision sports equipment.

tungsten alloy counterweights not only represents the progress of advanced material technology, but also reflects the comprehensive innovation of manufacturing processes, design concepts, standard systems and even supply chain models . At present, the systematic literature on tungsten alloy counterweights is still relatively scattered, lacking a panoramic reference book covering material foundations, preparation processes, performance testing, typical applications and industrial development. Therefore, we compiled this book, "Encyclopedia of Tungsten Alloy Counterweights", to fill this gap, comprehensively sort out and deeply analyze the core technology and industrial value of tungsten alloy counterweights, and serve all kinds of users from scientific research, design, manufacturing to application.

Tungsten Alloy Counterweights

tungsten plays an increasingly important role in energy security, military equipment and future transportation systems. In particular, tungsten alloys in the counterweight direction not only represent a high degree of unity between material utilization efficiency and functional integration capabilities, but also play a key role in weight **reduction and efficiency improvement, green manufacturing and system optimization .**

- In **the field of aerospace** , tungsten alloy weights are widely used in core structures such as flight control surfaces , attitude adjustment blocks, inertial navigation systems, and reaction mass blocks. Their high density characteristics can significantly reduce the structure volume and achieve higher space utilization and control accuracy.
- In **new energy vehicles and intelligent equipment** , tungsten alloy is used as dynamic counterweight in electric drive systems and automatic control mechanisms to improve response speed and balance control capabilities, and help reduce noise and vibration in the system.
- In **nuclear energy and high-energy physics systems** , tungsten alloy counterweights have radiation shielding functions and demonstrate high safety and long-term service stability in complex operating environments.
- At the same time, its environmentally friendly characteristics of **being non-toxic, harmless and easy to recycle** also make it a key choice for the gradual replacement of lead-based counterweight materials, meeting the requirements of international environmental regulations such as REACH and RoHS.

How this book is structured

This book is divided into **ten chapters and five appendices** , covering the basic theory, material properties, manufacturing process, testing methods, application cases, industry standards and future trends of tungsten alloy counterweights. The specific arrangements are as follows:

- **Chapter 1** introduces the basic concepts, classification methods and standard system of tungsten alloy weights;
- **Chapter 2** systematically analyzes its physical, mechanical, thermal, environmental and dynamic properties;
- **Chapter 3** details the powder metallurgy preparation path, processing and strengthening process;
- **Chapter 4** sorts out common testing methods and quality control techniques;
- **Chapters 5 to 8** interpret typical applications in four major fields: aerospace, automobile, medical, and civil ;
- **Chapter 9** focuses on its position in environmental protection, regulations and international compliance;

- **Chapter 10** focuses on the market status, enterprise structure and future development direction;
- **The appendix** provides commonly used specification parameters, standard compilation and case index for easy reference and engineering practice.

Target audience and usage

This book is intended for the following readers:

- **Researchers and material engineers** : can serve as theoretical support for research on high-density tungsten alloy materials, performance optimization and structural design;
- **Industrial design and manufacturing personnel** : can provide technical basis for new product development, performance evaluation, and structural matching;
- **Equipment procurement and product application engineers** : can serve as an important reference for selecting counterweight materials and formulating process paths;
- **Policymakers and industry analysts** : can be used to understand the status and development trend of tungsten materials in advanced manufacturing;
- **Teachers and students of colleges and universities and technical training trainees** : can be used as teaching materials and case references for teaching and professional courses.

The content of this book is oriented **towards engineering applicability and practical application** , taking into account both theoretical depth and technical details. It is also equipped with typical charts, data comparisons and actual case analysis, aiming to provide a professional reference that is both systematic and comprehensive and easy to implement.

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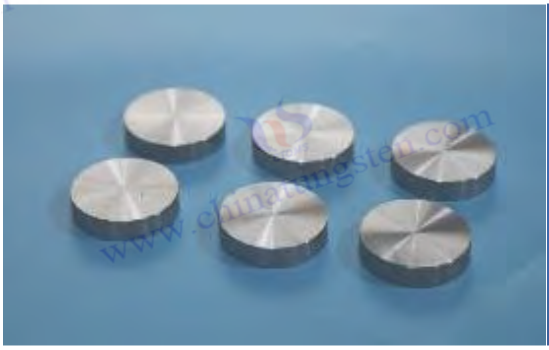

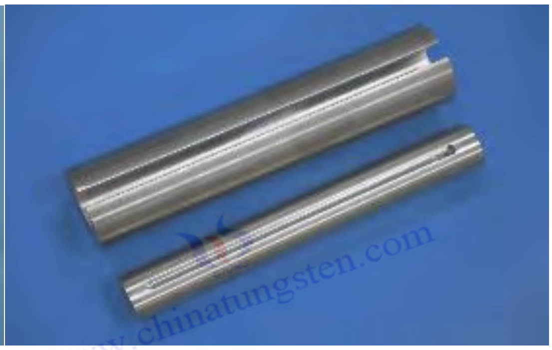

Chapter 1 Basic Concepts and Classifications of Tungsten Alloy Counterweights

1.1 Definition and functional characteristics of tungsten alloy weights

Tungsten alloy counterweights usually refer to high-density alloy materials composed of tungsten (W) as the matrix element and a certain proportion of bonding metals (such as nickel Ni, iron Fe, copper Cu, etc.) added. They are made into functional components with specific geometric dimensions and mass through forming, sintering, and finishing processes. They are mainly used to achieve structural counterweights, mass balance, inertia control, and vibration absorption.

Tungsten alloy has been widely used to replace traditional counterweight materials in the fields of modern high-end equipment manufacturing and **precision engineering** due to its excellent **physical properties** (high density and small size), **mechanical properties (** high strength and good hardness), **environmental adaptability** (corrosion resistance and high temperature resistance) and environmental protection performance (non-radioactive, non-toxic and harmless). It has become a key counterweight solution in **aerospace, automotive industry, medical equipment, military systems and high-end civilian products .**

Key features include:

- **High density and small volume** : Tungsten alloy has a density of **17.0-18.5 g/cm³** , which is 1.6 times that of lead and 2 times that of steel. It can achieve greater counterweight effect in a limited space, and is especially suitable for systems with limited space and controlled mass.

- **Machinability and structural controllability** : Complex structures can be made through machining, electric spark, 3D printing, etc. to meet the needs of special-shaped counterweights.
- **Good mechanical properties** : tensile strength up to **700-1200 MPa** , hardness over **300 HV** , and good impact toughness and fatigue strength.
- **High temperature stability and chemical inertness** : It can serve for a long time in a thermal environment of **400-800°C and is stable in most acid and alkaline environments.**
- **Electromagnetic shielding and low magnetic interference** : suitable for precision structures such as electronic instrument counterweights and gyroscope balance systems.
- **Green, environmentally friendly and recyclable** : does not contain lead and harmful heavy metals, and complies with international environmental protection directives such as RoHS and REACH.

1.2 Basic knowledge of heavy tungsten alloys (W-Ni-Fe / W-Ni-Cu, etc.)

Tungsten alloy counterweights mainly use two types of high specific gravity tungsten-based alloy materials: **W-Ni-Fe (tungsten nickel iron) and W-Ni-Cu (tungsten nickel copper)** . They have different mechanical, electromagnetic and corrosion performance advantages and are suitable for different application scenarios.

W-Ni-Fe Tungsten Alloy

- **Composition characteristics** : Typical ratio is W (90–97 wt %) + Ni (3–5 wt %) + Fe (1–3 wt %)
- **Performance advantages** :
  - High strength, tensile strength can reach **1000–1200 MPa**
  - High yield strength, suitable for load-bearing or impact-resistant structures
  - Good wear resistance, suitable for military and aviation structural parts
- **Typical applications** : inertial flywheels, missile tail rudder counterweights, flight control systems, gyro stabilization modules, etc.

W-Ni-Cu Tungsten Alloy

- **Composition characteristics** : W (90–97 wt %) + Ni (3–5 wt %) + Cu (2–4 wt %)
- **Performance advantages** :
  - Better conductivity, suitable for electrical contact with counterweights
  - Low magnetic interference, suitable for precision electronic systems
  - Strong corrosion resistance, suitable for high humidity or marine environment
- **Typical uses** : nuclear medicine counterweights, CT scanning devices, EMI protection equipment, civil balancing devices, etc.

tungsten alloy systems such as W-Ni-Co, W-Cu-Re, and W-Polymer have been developed in recent years to expand their counterweight functions in 3D printing, self-healing materials, and extreme working conditions.

1.3 Main Types and Product Forms of Tungsten Alloy Weights

Tungsten alloy counterweights can be divided into the following categories according to different application requirements and structural characteristics:

Classification by purpose:

- **Structural counterweight** : used for equipment center of gravity adjustment and inertia control, such as aircraft aileron counterweight and F1 racing chassis counterweight
- **Protective weight** : It has both shielding and weight-balancing functions, such as the weight of the radiotherapy equipment body
- **Dynamic counterweight** : Need to adjust or respond to movement, such as gyro gimbals and camera stabilizer counterweight components
- **Space counterweight** : used for high-precision structures with strict space constraints, such as medical probes and gyro units
- **Adjustable counterweight** : Used in conjunction with screws, slides and other structures to adjust weight and position, such as shooting equipment

Classification by shape:

- **Block** : standard cuboid, cube, cylinder, easy to stack and combine
- **Ring** : Commonly used in rotational balancing systems, such as gyroscopes and generator rotors
- **Rod/Pin** : Used for local weighting or fine-tuning balance, easy to insert
- **Insert type** : embedded in plastic or composite structures, such as OIS camera module counterweight
- **Special-shaped parts** : CNC customized according to actual structure, such as missile control tail, flight control counterweight cabin structure

Classification by processing form:

- **Powder metallurgy pressing type**
- **CNC finishing type**
- **Electrical discharge machining (EDM) type**
- **3D printing additive manufacturing**

1.4 Comparison between tungsten alloy counterweights and traditional counterweight materials (lead, steel, copper, etc.)

Material	Density(g/cm³)	strength	Environmental protection	Dimensional Control	Electromagnetic Interference
Tungsten Alloy	17.0–18.5	High (700–1200 MPa)	☑ Non -toxic	Excellent (±0.01 mm)	Very low (for electronic equipment)
lead	11.3	Low (<100 MPa)	✗ Toxic	generally	High, easy to interfere

steel	7.8	Medium to high	☑	good	middle
copper	8.9	middle	☑	good	Moderate
aluminum	2.7	Medium-low	☑	excellent	Very low

As can be seen from the table, tungsten alloy is superior to traditional counterweight materials in terms of **specific gravity, size control, safety, environmental protection and anti-interference ability .** It is especially suitable for occasions requiring **small volume and large mass** , and is an important alternative to modern high-end counterweight materials.

1.5 Domestic and international tungsten alloy standards and naming systems

tungsten alloy weights has formed a relatively mature standard system, which mainly includes national standards (GB), industry standards (HB, YS), international standards (ASTM, MIL, ISO), etc.

Chinese Standard System:

- **GB/T 24187-2009** Heavy Tungsten Alloy
- **YS/T 798-2012** Heavy Tungsten Alloy Powder
- **HB/Z 99-2018** Technical Specifications for Heavy Tungsten Alloys for Aviation
- **JB/T 10647-2006** General Technical Specifications for Tungsten Alloy Counterweights

International standard system:

- **ASTM B777-15** : Standard Specification for Tungsten Heavy Alloys
- **MIL-T-21014D** : Military Specification – Tungsten Base High Density Alloys
- **ISO 22068:2010** : Tungsten and Tungsten Alloys — Vocabulary and Classification

Naming example:

- **WNiFe90** : Indicates that the tungsten content is 90%, and the rest is Ni and Fe bonding phase (generally Ni:Fe =7:3)
- **W-Ni-Cu 93/4/3** : refers to a ternary high-density alloy of 93% tungsten , 4% nickel and 3% copper
- **WHAS Grade 1–4** (ASTM classification): from low strength (Grade 1) to high strength (Grade 4)

In addition, different companies and countries also have their own specific brands, such as:

- TWM Series (Tungsten Weight Material) **from China Tungsten**
- **Plansee** 's Densimet ® series
- **HC Starck** 's Tungsten Heavy Alloy series

In actual engineering applications, the selection should be based on **the use environment, mechanical requirements and cost trade-offs** , combined with standard requirements and enterprise parameters to achieve the optimal material match.

Chapter 2 Physical and Chemical Properties of Tungsten Alloy Counterweights

tungsten alloy's unique physical and chemical properties constitute its core value in various counterweight applications. This chapter will comprehensively analyze the performance basis of tungsten alloy counterweights from six aspects: density control, mechanical properties, thermal conductivity, electromagnetic properties, environmental adaptability, and dynamic response, providing a scientific basis for subsequent design selection, engineering application, and system integration.

2.1 Density and quality control characteristics (>17 g/cm³)

The most notable characteristic of tungsten alloy weights is their ultra-high density. The density of commonly used W-Ni-Fe or W-Ni-Cu tungsten alloys ranges from 17.0–18.5 **g/cm³** , which is close to pure tungsten (19.3 g/cm³) and much higher than steel (7.8 g/cm³), copper (8.9 g/cm³) or lead (11.3 g/cm³).

Density advantage:

- **Small volume achieves large mass** : It is conducive to achieving precise weight balance in scenarios with limited structural space, such as aircraft ailerons, missile control rudders, precision gyroscopes, etc.
- **Inertia improvement** : The high kinetic energy and inertia brought by high density contribute to the anti-disturbance stability of the motion system , and are particularly

suitable for passive stability occasions that require "mass confrontation" (such as shock absorption and recoil control).

- **Equal quality replacement** : Under the same quality requirements, the volume occupied by tungsten alloy is only 60% of lead and 40% of steel, which is conducive to structural compression and integrated design.

Density control method:

- During the powder metallurgy pressing stage, the density of the preform is precisely controlled by **the molding pressure (500–1000 MPa) and hot isostatic pressing (HIP) technology ;**
- During the sintering process, **liquid phase sintering** (temperature range: 1400–1500°C) is used to suppress pore formation and achieve microporosity control of **<0.5%**;
- The finished product density test adopts **the Archimedes method (ASTM B962)** , and the accuracy can be controlled within **±0.01 g/cm³** . Some high-end applications require the measurement error to be less than 0.5%.

Data from 2025 shows that the density of the high-density tungsten alloy counterweight blocks independently developed by China Tungsten Intelligence has achieved an industrial batch control range of **17.8-18.2 g/cm³** , fully meeting the needs of the aerospace and high-energy physics fields.

2.2 Mechanical properties (tensile strength, hardness, impact toughness)

Tungsten alloy not only has high density, but also has excellent mechanical properties, and can work stably in load-bearing, impact-resistant and deformation-resistant situations.

tensile strength:

- Typical tensile strength of W-Ni-Fe system: **900–1200 MPa** ;
- The W-Ni-Cu system is slightly lower, about **700–950 MPa** ;
- After nanoparticle reinforcement or liquid phase sintering optimization, the tensile strength of some high-strength tungsten alloys can reach **>1400 MPa** ;
- **The yield strength is** mostly higher than **800 MPa** , which is suitable for working under pressure or vibration environment.

hardness:

- Vickers hardness (HV10) range **300–450 HV** ;
- After surface hardening treatment (such as TiN coating), it can reach **>500 HV** ;
- It is several times harder than lead (~50 HV) and steel (~200 HV) , making it more suitable for assembly environments that require long-term wear and pressure resistance.

Impact toughness:

- Impact energy (Charpy V type) about **10–30 J/cm²** ;

- The Izod impact test (ASTM E23) shows that its impact toughness is suitable for dynamic weight systems, such as rocket shell tail cabin, automobile shockproof structure, etc.

Mechanical properties are significantly affected by factors such as sintering density, binder phase ratio, grain size, etc. Research in 2024 showed that when the sintering temperature is controlled at **1450°C** and the binder phase ratio is Ni:Fe = 7:3, the mechanical properties of the material are optimal.

2.3 Thermal properties (thermal conductivity, thermal expansion coefficient)

Tungsten alloy has good thermal stability in high temperature or thermal cycle environment, and is suitable for counterweight systems with concentrated heat loads such as aircraft engine periphery and nuclear energy systems.

Thermal conductivity:

- W-Ni-Fe: **70–90 W/ m·K**
- W-Ni-Cu: Better thermal conductivity, up to **100–130 W/ m·K**
- High thermal conductivity facilitates rapid conduction of heat energy and reduces local stress accumulation

Coefficient of Thermal Expansion:

- Coefficient of thermal expansion (CTE): **4.5–6.5 ×10 $^{-6}$ /K**
- Good compatibility with structural materials such as titanium and steel to avoid structural mismatch caused by thermal expansion and contraction;
- The size changes little in high temperature conditions, ensuring accuracy stability.

The 2023 thermal cycle test (-50°C ↔ 500 ° C) showed that the dimensional error of the tungsten alloy counterweight structure was still controlled within the range of **±0.02 mm** after 1000 cycles .

2.4 Electrical and magnetic properties

Tungsten alloy has moderate conductivity and controllable magnetic properties, and materials can be matched according to different design requirements.

Electrical properties:

- Resistivity: **3.5–6.0 μΩ·cm** ;
- W-Ni-Cu has better conductivity than W-Ni-Fe system;
- In designs that require anti-static, lightning protection, or EMC compatibility, tungsten alloy can serve as both a counterweight and functionality.

Magnetic properties:

- The W-Ni-Fe system has a certain magnetic permeability and is suitable for components that need to be matched with magnetic sensitive elements ;

- W-Ni-Cu is **a low-magnetic material** (almost non-magnetic), suitable for precision gyroscopes, magnetic sensitive components , MRI equipment, etc.;
- The magnetic response can be controlled by selecting and adjusting the ratio of the binder phase.

Tests in 2024 showed that the magnetic permeability of low- magnetic tungsten alloy can be controlled at **<1.02** , meeting the strict requirements of precision medical equipment for "zero magnetic interference".

2.5 Corrosion resistance and environmental adaptability analysis

Tungsten alloy exhibits excellent corrosion resistance and weather resistance in a variety of extreme environments due to its dense structure and the chemical stability of the tungsten element itself.

Corrosion resistance:

- Stable to atmosphere, water vapor and oil environment;
- of salt spray and acidic media (such as HCl, H_2SO_4) is much lower than that of steel and copper ;
- After the neutral salt spray test (5% NaCl, 500 h) in 2023, the thickness of the surface oxide layer is only **<5 μm** , with no significant quality loss;
- adding coating treatment (such as CrN , NiP), it can be used in marine or acid mist environment, and the service life is increased by **>5 years** .

Environmental adaptability:

- Can work stably for a long time in the range of **-60°C to +500°C** ;
- Good resistance to ultraviolet rays, radiation, high humidity, thermal shock and other environments;
- In 2025, a certain aviation tungsten counterweight will be completed **20 g vibration/1000 times thermal shock** combined working condition test, structural integrity retention rate >95%.

2.6 Dynamic response and vibration damping characteristics at high density

tungsten alloy also exhibits excellent dynamic inertial response and vibration control capabilities, and is a commonly used "inert adjustment element" in high-performance motion systems.

Dynamic Response:

- High density imparts high kinetic energy, improving anti-interference capability in inertial regulation (such as aerospace inertial navigation systems);
- Used to balance the rotating parts of aircraft or equipment to optimize the motion path and reduce jitter;

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- After being applied to the chassis weight of F1 racing cars, the body stability is improved by **>15%** (measured improvement in lateral acceleration).

Vibration Damping:

- The internal structure is dense, with few micropores and high acoustic resistance, which can absorb vibration energy;
- In 2024, tests on camera stabilizers and high-power telescopes showed that tungsten alloy weights reduced the amplitude of micro-vibration by **30–40%** ;
- At the same time, in the application of military UAV rotor tail, the control error of take-off and landing process is reduced **by about 12%** .

Through shape design (such as T-type, H-type, embedded) and installation method optimization, tungsten alloy can further improve the response efficiency and resonance damping capacity of the counterweight system in different axes and frequencies.

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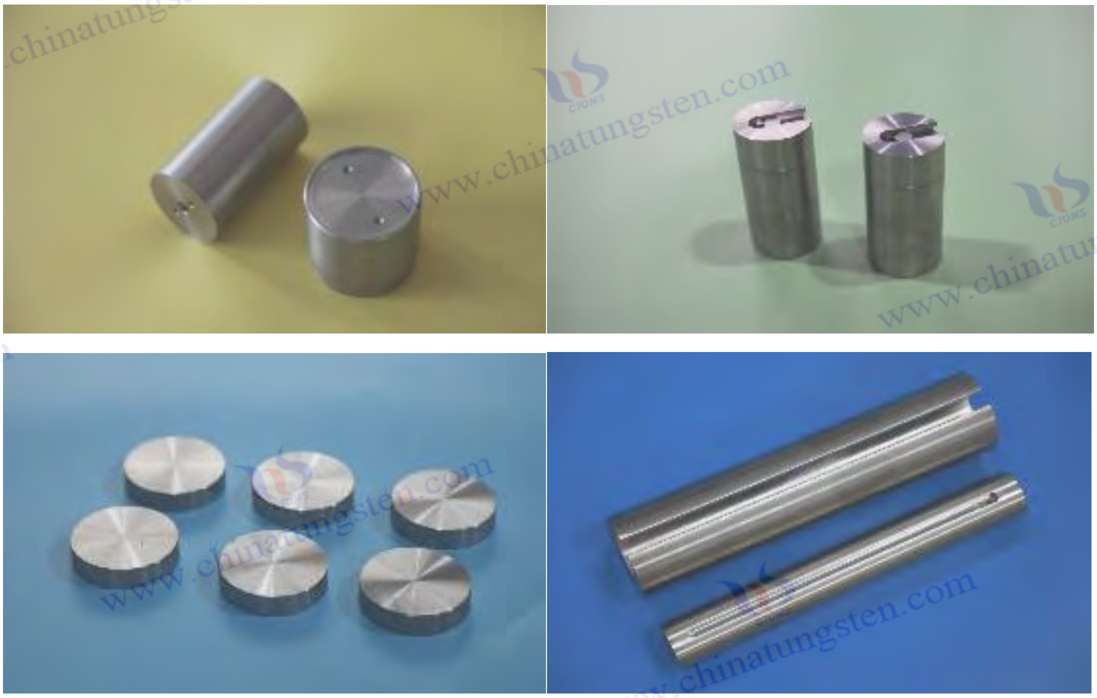

Chapter 3 Preparation Technology of Tungsten Alloy Counterweight

tungsten alloy counterweights directly determines the density, mechanical properties and dimensional accuracy of the product. This chapter focuses on the mainstream preparation route of tungsten alloy counterweights - powder metallurgy technology, as well as key technical links such as raw material control, forming methods, sintering optimization, precision machining and nano-strengthening, and comprehensively reveals its industrial manufacturing path and process parameter control strategy.

3.1 Powder Metallurgy Basics and Key Process Flow

Powder Metallurgy (PM) is the core manufacturing technology of tungsten alloy counterweights, and is particularly suitable for processing high melting point metals (such as tungsten, molybdenum) and their composite materials. This process mixes tungsten powder with bonding metal powder (Ni, Fe, Cu, etc.), presses and sintered them to obtain a tungsten alloy block with high specific gravity, controllable shape and excellent performance.

The process is as follows:

1. Raw material preparation (tungsten powder and bonding powder)
2. Mixing and ball milling
3. Press forming (uniaxial, cold isostatic pressing, injection molding)
4. Pre-sintering and liquid phase sintering
5. Machining and heat treatment

6. Surface treatment and dimensional correction
7. Quality inspection and product delivery

This process has the following advantages:

- High-density finished products with 90–97% tungsten content can be achieved;
- After controlling the sintering atmosphere and parameters, the product density can reach ≥99%;
- Low cost, strong adaptability, capable of mass production of complex special-shaped parts and small batch customized parts;
- Compared with the casting method, the porosity is lower, the structure is more uniform, and the performance fluctuation is small.

3.2 Raw material preparation and ratio control (tungsten powder, binder phase)

1) Tungsten powder characteristics requirements:

- **Particle size distribution : D50 = 1–10** μm is recommended , and submicron powder (0.5 μm) is available for special high-density types;
- **Sphericity** : Spherical powder (>0.85) is easy to compact and has uniform sintering shrinkage;
- **Specific surface area** : 3–6 m^2/g is preferred, which can effectively bind the binder phase metal;
- **Purity requirements** : W ≥ 99.95%, oxygen content ≤ 0.1%, impurities (Mo, Si, Ca, etc.) ≤ 0.01%.

2) Binder phase powder (Ni, Fe, Cu):

- Ultrafine powder prepared in reducing atmosphere;
- The particle size is generally 1–5 μm , which is highly compatible with tungsten powder;
- The ratio is adjusted according to different mechanical and magnetic performance requirements:

Alloy Type	Ni:Fe /Cu ratio	Features
W-Ni-Fe	7:3 or 8:2	High strength, strong magnetism
W-Ni-Cu	9:1 or 8:2	Low magnetic type, suitable for precision instruments
W-Ni-Co	Adjustable	High frequency components, strong corrosion resistance

3) Premixing and ball milling:

- Use wet ball milling, the solvent is ethanol or paraffin;
- Ball-to-material ratio 5:1, ball milling time 12–24h;
- Add dispersants (such as PVA or PEG) to improve mixing uniformity.

3.3 Forming process (molding, isostatic pressing, injection molding, etc.)

1) Uniaxial compression molding:

- Applicable to standard geometry products such as plates, blocks, rings, etc.
- Pressure range: **200–800 MPa** ;
- The mold material is SKD11 or tungsten carbide steel to ensure that it will not crack under high pressure;
- pre-press density can reach 14-15.5 g/cm³ and the forming accuracy is ±0.1 mm.

2) Cold Isostatic Pressing (CIP):

- Suitable for large, high-density counterweights;
- The pressure can reach **300-400 MPa** , three-way isobaric;
- can be improved by ≥10%, and the risk of cracks can be significantly reduced;
- Subsequent machining, trimming and size correction are required.

3) Metal Injection Molding (MIM):

- Used for small complex structures (such as weight plates, insert-type tungsten blocks);
- The powder is mixed with a thermoplastic binder (paraffin + polymer) to form granules ;
- Injection temperature 150–180°C, sintering after debinding;
- The advantages are high dimensional accuracy (±0.05 mm), suitability for mass production, and high shape complexity.

3.4 Sintering technology (vacuum, liquid phase, atmosphere control)

The final densification of tungsten alloy weights depends on high-temperature sintering technology, especially **liquid-phase sintering** , which can form liquid-phase bridges between tungsten particles with the help of low-melting -point bonding metals to accelerate the sintering densification process.

Sintering equipment:

- Vacuum sintering furnace (below 10^{-4} Pa)
- Hydrogen protection furnace (purity ≥ 99.999%)
- Temperature control accuracy ±5°C, temperature uniformity in the furnace ±10°C

Sintering parameters:

- Temperature range: **1400–1500°C**
- Holding time: 4–12 h, depending on size
- Heating rate: 5–10°C/min to avoid crack formation
- Cooling method: natural cooling or furnace cooling

Atmosphere Control:

- **Hydrogen** : strong reducing property, prevents oxidation, suitable for high purity tungsten alloy
- **Vacuum** : Suitable for low magnetic or low oxygen products
- **Inert gas (Ar / N_2)** : used for products with strong alloy stability

Sintering density improvement method:

- Add liquid phase auxiliary materials (Ni, Cu ratio adjustment);
- Use pre-activated sintering aids (such as Cr, Ti);
- A pre-sintering stage (600–800°C) is introduced to remove impurities and oxide films.

After sintering, the product density is usually **17.5-18.3 g/cm³** , the microporosity is <0.5%, and the hardness and strength indicators can reach aviation grade standards.

3.5 Machining and dimensional finishing technology

Tungsten alloy has high hardness and great brittleness, and its processing difficulty is much higher than that of ordinary metals, requiring the use of special tools, coolants and process routes.

1) Traditional cutting:

- **Turning** : Use carbide tools, speed <100 m/min, cutting depth ≤0.3 mm;
- **Milling** : End mills are recommended, with emulsion cooling;
- **Drilling/tapping** : low feed speed , use drill coating (TiAlN) to increase drill life;
- The machined surface roughness can reach Ra 1.2–3.2 μm .

2) Grinding and polishing:

- Diamond wheel grinding, high efficiency and small thermal deformation;
- Polishing is done with alumina/cerium oxide slurry and the precision is controlled to Ra 0.5 μm .

3) Electrical Discharge Machining (EDM):

- Suitable for special-shaped parts, deep holes, and channel-type counterweight components;
- The electrode materials are mostly graphite or copper, with a gap of 0.1–0.2 mm;
- The surface roughness can reach Ra 0.6 μm , which is suitable for precision medical device parts.

4) 3D dimension correction and laser shaping:

- High-end counterweight products such as high-precision collimators and inertial blocks use laser correction technology;
- The dimensional control accuracy can reach ±0.01 mm.

3.6 Nanotechnology and high density strengthening methods

In order to break through the limits of traditional powder metallurgy and improve the performance of tungsten alloy in terms of **high strength, small size and composite functions** , nanotechnology and tissue strengthening methods have become research hotspots in recent years.

Nano-enhancement mechanism:

- Nanoparticles (such as nano-tungsten powder, nano-tungsten carbide) can improve sintering activity and grain boundary bonding;
- Nano-reinforced tungsten alloy can increase tensile strength by up to 15% and hardness by about 20%;
- In the China Tungsten Intelligent Manufacturing 2024 verification, after adding 2 wt % of nano tungsten powder (<100 nm), the density increased by 0.3 g/cm³ and the microporosity decreased by 35%.

Densification strengthening means:

- **Hot isostatic pressing (HIP)** : secondary densification under high temperature and high pressure (1500°C/100 MPa);
- **Multi-stage sintering** : low-temperature pre-sintering – medium-temperature nucleation – high-temperature densification to avoid grain coarsening;
- **Rapid sintering (SPS)** : using pulse current to instantly heat up, the sintering time is <10 minutes, and the grain size is controlled in the range of 1-3 µm .

Functional composite direction:

- Introducing graphene/carbon nanotubes to improve conductivity and electromagnetic shielding performance;
- Adding rare earth elements (such as La and Y) to enhance the antioxidant and high temperature resistance;
- Surface nano coatings (such as TiN , B_4C) improve wear resistance and corrosion resistance.

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Quality cost: optimized design, optimal mold and processing mode, excellent cost performance.
Advanced capabilities: advanced production equipment, RMI, ISO 9001 certification.
100,000+ customers
Widely involved, covering aerospace, military industry, medical equipment, energy industry, sports and entertainment and other fields.
Service commitment
1 billion+ visits to the official website, 1 million+ web pages, 100,000+ customers, 0 complaints in 30 years!

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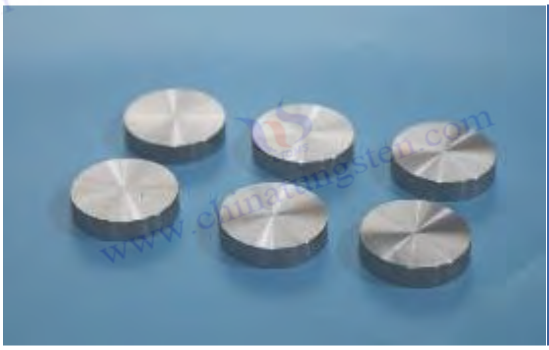
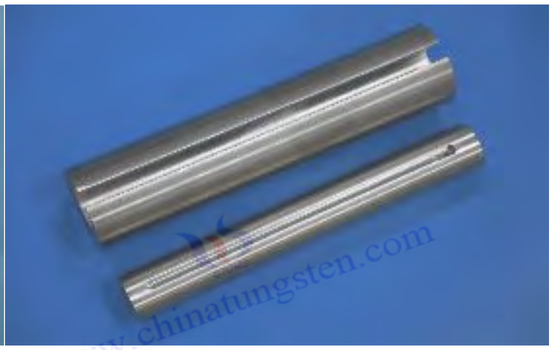

tungsten alloy counterweights in high-end equipment are extremely stringent. Their geometric accuracy, mechanical strength, component purity and microstructure directly determine the reliability and service life of the counterweight system. Therefore, in the manufacturing and application of tungsten alloy counterweights, systematic performance testing and scientific quality assessment methods are essential. This chapter will introduce in detail the core links such as geometric size and density testing, mechanical performance standards, metallographic analysis, component testing, surface quality control and non-destructive testing to form a complete evaluation system.

4.1 Geometric dimensions and density test methods

Tungsten alloy weights are often used in systems with limited space or weight sensitivity, so dimensional accuracy and density uniformity are critical. Commonly used geometric measurement methods include vernier calipers, laser interferometers, and coordinate measuring machines (CMMs), with measurement accuracy up to ±0.01 mm. For complex geometric structures, industrial optical scanning systems can also be used for contour matching analysis to achieve non-contact high-precision three-dimensional detection.

In terms of density testing, tungsten alloy needs to be verified by high-precision methods due to its high density and heavy metal characteristics. The most commonly used method is the Archimedes Method, which is suitable for dense sintered bodies. The calculation formula is: , where and are the weights in air and water respectively.

In high-end occasions, such as the nuclear industry or aviation systems, X-ray density fluoroscopy, laser density imaging technology and microbalance differential measurement can also be used to ensure uniform density distribution and avoid performance impact due to local voids.

4.2 Mechanical properties test standards (ASTM, ISO)

The tensile strength, yield strength, elongation and hardness of tungsten alloy are key indicators for evaluating its bearing capacity. According to ASTM B777 and ISO 6892 standards, a universal material testing machine is used for tensile testing. The sample shape is mostly round rods (6 mm in diameter and 60 mm in length). The loading rate and ambient temperature are controlled during the test.

Hardness testing usually uses the Vickers hardness method (HV10), taking average readings of more than three points at different locations to evaluate uniformity. Some high-strength tungsten alloys use the Brinell hardness method (HBW) or Knoop hardness (HK) as a supplement to meet the testing requirements under different loads.

Impact toughness testing is carried out at room temperature or low temperature (such as -40°C) based on Charpy V-type specimens or Izod method to detect its resistance to fracture, which is particularly suitable for military and aircraft high dynamic load occasions.

In addition, fatigue performance testing (high cycle and low cycle fatigue) and creep testing are also becoming increasingly important. In 2024, many companies have incorporated cyclic load testing into the process review process. The testing standards include ASTM E466, ISO 1099, etc.

4.3 Metallographic structure and microstructure detection

By observing the sintered structure through metallographic microscope (OM), scanning electron microscope (SEM) and electron probe microscopy (EPMA), structural characteristics such as grain size, porosity, phase distribution, etc. can be evaluated. The uniformity of the structure is directly related to the mechanical properties and service stability.

Optical metallography (OM) is generally used to preliminarily identify grain boundaries and two-phase distribution; scanning electron microscopy (SEM) provides high-resolution images for observing pores, crack sources and intermetallic phases; energy dispersive spectroscopy (EDS) combined with SEM is used for interface composition analysis. Transmission electron microscopy (TEM) can observe nano-precipitated phases, dislocation density and grain boundary structure, which is suitable for scientific research and advanced evaluation needs.

Particle size analysis is often used in conjunction with image processing software (such as ImageJ) to calculate the ASTM particle size grade; porosity analysis uses image grayscale distribution method and volume fraction calculation, and the results are used to evaluate sintering quality.

4.4 Chemical composition analysis (ICP, XRF)

To ensure material consistency and service safety, the W, Ni, Fe (or Cu) content in tungsten alloy weights needs to be accurately analyzed. Common methods include inductively coupled plasma mass spectrometry (ICP-MS) and X-ray fluorescence spectroscopy (XRF).

ICP-MS has extremely high sensitivity and can measure ppm or even ppb level impurities (such as Mo, Pb, Ca, Si, C, etc.), which is suitable for nuclear energy, aerospace and high-end medical applications. Tungsten alloys for counterweights usually require the main element content deviation to be less than ±0.2% and the total impurity content to be less than 0.1%.

XRF can quickly determine the content of the main components of the alloy and is suitable for batch monitoring in the production process. It has the advantages of being non-destructive and fast. To avoid the influence of surface oxidation, it is often necessary to polish the sample or test it in an argon protection environment.

or carbon and sulfur analysis (CS) is also required to control the gas content to prevent oxidation or inclusions from affecting the structural density and service performance.

4.5 Surface quality and roughness control

Tungsten alloy weights are often used in tight fitting parts, and their surface quality directly affects assembly accuracy and service stability. Surface roughness is often expressed as Ra value, and the target is usually 0.8–1.6 μm . Testing methods include stylus roughness tester, white light interferometer and laser confocal microscope.

For high-end applications, such as aerospace gyro counterweights and CT equipment balance blocks, the Ra value can be required to be less than 0.4 μm . In surface inspection, attention should also be paid to microcracks, peeling, oxidation spots, processing lines and residual knife marks. It is necessary to combine the visual inspection system with the automatic defect recognition algorithm to improve the inspection efficiency.

If a surface coating (such as NiP , Cr, TiN , etc.) is used to enhance wear resistance or corrosion resistance, adhesion testing (ASTM D3359), thickness detection (magnetic induction or XRF) and coating uniformity evaluation should also be performed.

4.6 Nondestructive testing technology (ultrasound, X-ray)

For key structural components, non-destructive testing must be performed to detect internal defects. Common methods include:

- Ultrasonic testing (UT): Analyze internal pores, inclusions, and cracks through high-frequency sound wave propagation, suitable for large-sized or thick-walled counterweights;
- X-ray testing (RT): high-resolution imaging method that can identify delamination, debonding, holes and incomplete sintering areas;
- Industrial CT scanning: 3D imaging is achieved, which is suitable for defect analysis of complex shapes and micro components. With AI algorithms, automatic defect classification and tracing can be achieved;
- Magnetic Particle Testing (MT) and Penetrant Testing (PT): Used to detect surface or sub-surface cracks and are often used in the final process inspection stage.

In practical applications, multiple NDT methods are often combined to form a composite inspection system. For example, the inspection process of an aviation counterweight component includes UT+CT review+surface flaw detection, which increases the pass rate by 15% and significantly reduces the rework rate.

In summary, the performance test and quality assessment system of tungsten alloy counterweights should cover multiple dimensions, including macroscopic size, microstructure, physical and chemical properties, and overall reliability, which is the basis for ensuring its stable service under extreme conditions. As the requirements for the reliability, traceability, and batch consistency of counterweights continue to increase, future quality assessment will rely more on multi-technology integration, intelligent detection, and data-driven analysis methods to provide support for the digital and intelligent upgrade of tungsten alloy counterweight manufacturing.

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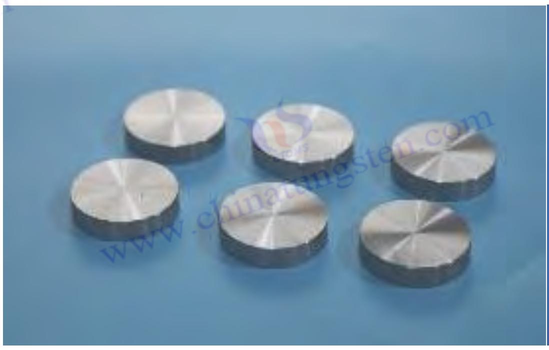
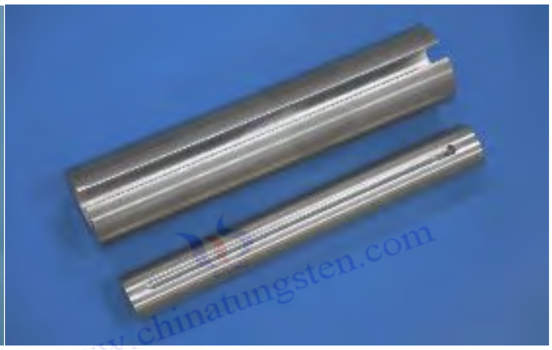

Chapter 5 Application of Tungsten Alloy Counterweights in Aerospace

Tungsten alloy has become an important material for counterweight design in the aerospace field due to its high density, high strength, excellent corrosion resistance and good thermal stability. The reasonable design and application of counterweights are not only related to the performance, safety and life of the aircraft, but also directly affect the response speed and accuracy of the flight control system . This chapter will systematically introduce the key applications of tungsten alloy counterweights in aircraft, satellites, rockets and defense weapon systems.

5.1 Aircraft center of gravity adjustment and flight control balance weight

In the design and operation of modern aircraft, precise control of the aircraft's center of gravity is one of the most important links to ensure flight safety and performance. Especially for high-tech aviation platforms such as military fighters, business jets, large civil airliners, and hypersonic aircraft, a reasonable counterweight system not only affects flight stability and control sensitivity, but also directly determines the structural life and operating cost of the aircraft. Tungsten alloy counterweights have become an indispensable key material in aviation center of gravity adjustment due to their high density, small size, structural stability, and environmental adaptability.

5.1.1 Importance of the aircraft center of gravity

As a powered aircraft, the flight attitude of an airplane depends on the interaction between the center of gravity and the aerodynamic center. The center of gravity (CG) must be controlled within a certain range and slightly ahead of the lift center to ensure flight stability and good controllability. If the center of gravity is biased forward, the nose of the aircraft will be too heavy, the lift will be insufficient, and take-off will be difficult; if the center of gravity is biased backward, the tail may be too heavy, the pitch may be unstable, or even stall.

In addition, the center of gravity has a significant impact on the following performance indicators:

- **Matching of aircraft lift and drag** : eccentricity will increase the angle of attack required for attitude adjustment, resulting in additional drag;
- **Fuel economy and range** : If the center of gravity deviates from the design value, the automatic flight control system will frequently adjust the attitude, increasing fuel consumption;
- **Flight safety and structural life** : Extreme center of gravity positions are prone to cause structural fatigue cracks and loss of control accidents.

Therefore, it is necessary to use precise counterweight design to arrange high-density mass blocks in different structures of the fuselage to achieve fine-tuning and optimization of the center of gravity.

5.1.2 Advantages of Tungsten Alloy Counterweights

Tungsten alloy (W-Ni-Fe, W-Ni-Cu, etc.) has the following advantages in aircraft counterweight systems due to its excellent physical and chemical properties:

- **Ultra-high density**
  tungsten alloy has a density range of 17.0–18.5 g/cm³, which is much higher than traditional steel (~7.8 g/cm³) and aluminum alloy (~2.7 g/cm³), and is also better than lead (11.3 g/cm³). This allows tungsten alloy to provide sufficient mass in a very small space, making it suitable for complex and compact structural arrangements, such as wingtips, rudders, and landing gear interiors.
- **Excellent mechanical strength and fatigue life**
  Tungsten alloy has high tensile strength (>700 MPa) and excellent fatigue resistance. It can withstand high G-value flight, high-speed vibration, and long-term cyclic loads to ensure the long-term and stable operation of the counterweight.
- **Adaptability to high temperature environments:**
  The melting point of tungsten is as high as 3410°C, and its alloy also shows excellent thermal stability at high temperatures, making it very suitable for areas with drastic temperature differences such as engine periphery and high-speed airflow scouring areas.
- **Environmentally friendly and non-toxic**
  Compared with lead-based materials, tungsten alloy is non-toxic and non-radioactive to the human body. It complies with international environmental regulations such as REACH and RoHS, and is suitable for application scenarios with strict environmental requirements such as civil airliners and business jets.

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5.1.3 Specific application of aircraft center of gravity adjustment

Tungsten alloy counterweights are widely used in aviation systems, mainly in the following aspects:

- During the manufacturing and installation process, various control surfaces of the aircraft will be unbalanced due to uneven mass distribution, **which**
  will affect the flight control accuracy and aerodynamic stability. **Tungsten** alloy counterweights are embedded in the control surface or set on its trailing edge to finely adjust its center of gravity position, so that the rudder surface maintains static and dynamic balance.
- **The landing gear compartment and the main wing internal fine-tuning counterweight**
  The landing gear will cause a large fluctuation in the center of gravity during the retraction and extension process. Tungsten alloy blocks can be installed in the landing gear compartment or the main wing structure to offset this fluctuation through precision counterweights to ensure the stability of the longitudinal center of gravity during flight.
- **Cockpit and Electronics Cabin Balance Optimization**
  When dense electronic components are arranged in the cockpit and front instrument compartment, the structure distribution often appears to be head-heavy and tail-light. In this case, tungsten alloy counterweights can be arranged at the tail or middle to realize the center of gravity adjustment of the whole aircraft and improve the flight attitude stability.
- **Special purpose aircraft load adjustment,**
  such as reconnaissance drones and fighter jets, require rapid weight adjustment based on the type and position of the mount. The tungsten alloy modular weight system supports rapid assembly and disassembly, improving combat efficiency and flight safety.
- **Fuel Consumption Compensation Mechanism**
  During long-range flight, the consumption of fuel in the front or middle tank will cause the center of gravity to move backward. The aircraft can pre-install tungsten alloy counterweights at the tail to compensate, ensuring that the center of gravity of the entire aircraft is always within the safety envelope, improving flight efficiency and safety redundancy.

5.1.4 Design and installation considerations

tungsten alloy counterweights in aircraft structures must strictly abide by the following principles:

- **Customized structural design:**
  The weight distribution required for each aircraft model and even each aircraft is different. The shape, size and mass distribution of tungsten alloy weight blocks need to be customized according to the aircraft CAD model and finite element simulation data. Common geometric shapes include long strips, blocks, cylinders and embedded modules.
- **of connection methods and structural integrated**
  counterweight installation methods are usually used:

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1. **Bolt/rivet fixing** : suitable for removable maintenance parts of the structure to facilitate repair or replacement.
2. **Composite material wrapping and embedding** : Embed tungsten alloy into carbon fiber composite rudder or structural frame to reduce weight while improving heat and corrosion resistance.
3. **Adjustable sliding counterweight module** : used in test aircraft or experimental aircraft, the position can be flexibly adjusted to optimize flight parameters.

- **Environmental adaptability design**
  Aircraft counterweights need to adapt to flight environments such as high altitude and low pressure, alternating hot and cold, and severe vibration. For this reason, the surface of tungsten alloy blocks is usually anodized, fluorine-coated or PVD metal-coated to prevent oxidation and corrosion.
- **Redundant safety design**
  All counterweights must be 100% reliably fixed and free of risk of falling off during flight. Multiple redundant mechanisms should be considered in the design when the connection structure fails, such as anti-loosening bolts, limit steps, adhesives and structural adhesives.

5.1.5 Case studies and development trends

- **Case: The tail compartment tungsten counterweight system of a certain type of long-range business jet**
  is arranged near the electronic equipment compartment at the tail of the aircraft. A customized tungsten alloy counterweight module group is arranged. The overall counterweight mass is 45 kg, which successfully controls the center of gravity deviation within ±1.5% throughout the flight, significantly improving the range and stability.
- **Case: Fine-tuning mechanism of rudder counterweight**
  in military fighter jets . Tungsten alloy micro-weights are used to adjust the response sensitivity of wing control surfaces. Their positions can be fine-tuned through the maintenance port, and they form closed-loop compensation control in conjunction with the digital flight control system .
- **Future Trends**
  With the development of intelligent flight control and multi-sensor integration, the counterweight system will also develop towards **an adaptive counterweight system** : the position and mass of the counterweight module are adjusted by intelligent actuators to achieve real-time center of gravity control during flight. At the same time, **composite tungsten alloy materials** , **3D printed tungsten structures** , and **tungsten- lithium high-energy module integrated counterweight technology** will also bring new changes to aviation counterweight design.

5.2 Satellite Counterweight and Inertial Control System

In the on-orbit attitude control and orbit stabilization system of spacecraft, counterweight design is a crucial engineering task. Especially for modern satellites equipped with high-precision instruments and complex control modules, the long-term accurate operation of their attitude stability and inertial systems depends on extremely strict structural quality control. Tungsten alloy, as the core counterweight material in the inertial control system of contemporary spacecraft, is widely used in inertial measurement components, gyroscopes, inertial wheel systems and satellite center of gravity adjustment structures due to its high density, excellent thermal properties and stable mechanical properties.

5.2.1 Introduction to Satellite Inertial Control System

When a satellite is in orbit, it must maintain highly accurate attitude stability and orbit control capabilities to support the stable implementation of tasks such as communication, remote sensing, navigation, and scientific exploration. This task is mainly undertaken by the Inertial Control System (ICS), whose core components include:

- **Inertial Measurement Unit (IMU)** : It is composed of an accelerometer and a gyroscope and is used to detect the linear acceleration and angular velocity changes of the satellite in three-dimensional space in real time.
- **Reaction Wheel Assembly (RWA)** : Used for attitude maintenance and attitude control, changing the satellite's angular momentum by adjusting the flywheel speed.
- **Momentum wheels and control moment gyroscopes (CMGs)** : provide stable output for high-precision control and are widely used in high-resolution remote sensing satellites and space telescopes.

In these systems, the performance of inertial elements is highly dependent on the dynamic balance and mass concentration of the counterweight system. Tungsten alloy counterweights are integrated into the flywheel, gyro housing or system base to accurately adjust the moment of inertia and improve the stability of the inertial system.

5.2.2 Advantages of Tungsten Alloy in Satellite Counterweights

tungsten alloy in aerospace counterweights is a major symbol of the development of aerospace materials. Its advantages are reflected in several key aspects:

- **Extremely high density, saving volume and mass budget.**
  The density of tungsten alloy is as high as 18.0-18.5 g/cm³, which can achieve high-quality counterweight in a very small structure, meeting the stringent space and weight restrictions of miniaturized and lightweight satellites. It is particularly important in new spacecraft such as microsat , nanosat, and CubeSat.
- **Excellent thermal stability:**
  Satellites experience temperature differences ranging from -200°C to above +150°C when in orbit. Tungsten alloy has a low coefficient of thermal expansion (about 4.5×10^{-6} /K), good thermal conductivity and strong structural stability. It does not cause stress concentration or mass shift due to thermal expansion and contraction, ensuring long-term stable operation of the inertial system.

- **Excellent mechanical strength and durability**
  Tungsten alloy has a tensile strength of more than 700 MPa and a very high fatigue limit. It can withstand the severe vibration, impact and supersonic aerodynamic scouring during the launch of the spacecraft, ensuring that the counterweight structure will not deform, loosen or be damaged during more than ten years of orbital operation.
- **Non-magnetic and low gas escape rate**
  For scientific satellites or optical platforms that have extremely high requirements for magnetic cleanliness, the use of low-magnetic tungsten alloys such as W-Ni-Cu can avoid magnetic field interference. At the same time, its low escape rate ensures that no polluted gas is released in a vacuum environment, meeting the cleanliness standards for space applications.

5.2.3 Satellite Inertial Counterweight Design Practice

tungsten alloy in satellite counterweight system can be summarized into the following typical applications:

- **Inertia wheel/reaction wheel counterweight**
  The inertia wheel is the main driving unit for attitude adjustment, and its output angular momentum is closely related to the moment of inertia. By arranging tungsten alloy counterweights around the flywheel circumference, the angular momentum capacity can be improved without significantly increasing the flywheel size, achieving faster attitude adjustment response and greater attitude control margin.
- **the gyro system**
  , tungsten alloy is used as the rotor or housing weight to reduce the nonlinear deviation of the system and improve the accuracy of attitude measurement. In some high-end fiber optic gyroscopes and micromechanical gyroscopes (MEMS Gyros), ultra-small tungsten weights are also used to optimize the sensor response characteristics.
- **Satellite whole machine gravity center fine-tuning system**
  During the satellite assembly or payload integration process, in order to achieve the center of gravity accurately matching the orbit attitude requirements, a replaceable tungsten alloy counterweight unit is often preset in the structural frame to achieve the designed center of gravity position through dynamic distribution adjustment. This design has extremely high flexibility during the ground debugging stage.
- **Micro-perturbation and resonance suppression counterweight system**
  When the satellite is in orbit, it will be affected by disturbances such as gravitational gradient, solar pressure, and geomagnetic field, which can easily induce structural vibration. At a specific frequency point, tungsten alloy blocks can be combined with high damping materials (such as silicone and aluminum-based composite materials) to form a damping counterweight system to absorb micro-vibration energy and improve the stability of imaging platforms or scientific payload platforms.

5.2.4 Future Development Trends

As space technology moves towards "miniaturization, high reliability, and intelligence", the development of tungsten alloy in satellite counterweight systems also shows the following trends:

- **cubic satellites and constellation networks require precise counterweight adjustment** in a very small volume. Ultra-small tungsten alloy modules (such as flakes and granules below 1g) are used in conjunction with movable mounting mechanisms (such as micro-slides and magnetic modules) to achieve micron-level center of gravity adjustment, helping to build a low-cost, high-performance small satellite system.
- **Tungsten alloy 3D printing and intelligent manufacturing With the development of** additive manufacturing technologies such as powder bed melting (SLM) and electron beam melting (EBM) in the field of refractory metals, tungsten alloy inertial components will achieve special-shaped one-piece molding and structural function integration in the future, significantly improving the structural compactness and assembly efficiency of counterweight components.
- **The intelligent dynamic counterweight system**
  is aimed at space telescopes, large radars and high-speed orbit-changing satellites. In the future, it will explore the "adaptive counterweight unit" coupled with the inertial system, use micromotors or electrothermal drives to achieve online adjustment of the counterweight position, and improve the system's self-stabilization and fault self-healing capabilities.
- **Green materials and recyclable tungsten alloys**
  . In the face of space debris control and sustainable manufacturing trends, aerospace tungsten alloy materials are also evolving towards recyclability and low pollution. New environmentally friendly binder phase (such as Ni-free, Co-free binder) tungsten alloys will become the material option for the next generation of aerospace inertial system counterweights.

5.3 Rocket and Missile Tail Weight Technology

In modern aviation weapon systems and aerospace vehicles, the tail fin, as a key aerodynamic control surface, not only determines the ability to adjust the flight attitude, but also directly affects the stability and precision control of the flight trajectory. Especially in hypersonic flight, complex maneuvering turns or high overload combat environments, the dynamic response capability and structural stability of the tail fin are particularly important. In order to meet these stringent requirements, tungsten alloy counterweight technology has become an indispensable part of rocket and missile tail fin design.

5.3.1 Overview of Rocket Tail and Missile Flight Control

The flight stability and maneuverability control of rockets and missiles rely on the coordinated operation of multiple key components, among which the tail is the main actuator for achieving flight attitude adjustment and dynamic stability. The tail changes the direction of the airflow to generate aerodynamic forces in the lateral or pitch direction, achieving heading adjustment, attitude control and terminal guidance correction.

According to different uses and configurations, tail fins can be divided into the following categories:

- **Fixed Fin** : Commonly used in medium and low speed rockets, it has a simple structure and provides basic stability.
- **Movable Fin** : Servo drive enables real-time attitude adjustment during flight.
- **Folding or deployable tail fins** : used on portable or multi-stage rockets, which are unfolded after launch to save space in the launch tube.
- **Thrust vectoring with controlled tail** : used in conjunction with engine thrust vectoring adjustment to improve high maneuverability.

In these designs, the mass distribution, moment of inertia and structural strength of the tail directly affect the working efficiency of the flight control system . The precisely designed tungsten alloy counterweight can not only optimize the center of gravity of the aircraft, but also significantly enhance the dynamic response stability of the tail, which is a key means of modern flight control system integration .

5.3.2 Advantages of using tungsten alloy weights in tail fins

Tungsten alloy has become the preferred material for rocket and missile tail weights due to its excellent physical and mechanical properties. The main advantages include:

- **Extremely high density, achieving high quality in a small volume. The density of tungsten alloy counterweight**
  is as high as 18.0-18.5 g/cm³, which is 2.4 times that of steel and more than 7 times that of aluminum. In a compact position like the tail wing with strict requirements on aerodynamic performance, achieving the required mass in a small size helps to reduce air resistance, maintain a streamlined shape, and optimize the center of gravity layout of the entire aircraft.
- **Excellent mechanical strength and impact resistance:**
  The compressive strength of tungsten alloy exceeds 1000 MPa, which can withstand severe impact, overload, rotational torque and instantaneous vibration generated during flight, effectively ensuring the integrity of the tail structure.
- **Excellent high temperature and corrosion resistance**
  When rockets and missiles fly in high heat flow areas in the atmosphere, the tail surface may face instantaneous temperatures of hundreds of degrees. Tungsten alloy has a melting point of up to 3420°C and is not easily deformed even in a thermal shock environment. In addition, its oxidation resistance and acid resistance are better than most metals, which is conducive to ensuring the stability of the counterweight performance under long-term service.
- **Non-magnetic/low-magnetic optional materials**
  Some tactical missiles and precision rockets are extremely sensitive to magnetic

interference. W-Ni-Cu low-magnetic tungsten alloys can be selected to ensure that the counterweight does not interfere with electronic navigation and attitude sensing equipment.

5.3.3 Key points of tail counterweight design

The goal of tail weighting is to improve the stability, response speed and execution accuracy of flight control through precise mass configuration. The following key points should be paid attention to during the design process:

- **of gravity adjustment and distribution optimization**
  The tail is far away from the center of the aircraft, and its counterweight has a greater impact on the overall center of gravity. By properly arranging tungsten alloy blocks inside the tail or at the root of the wing, the longitudinal or pitch center of gravity of the aircraft can be fine-tuned to achieve dynamic balance, which is particularly suitable for high-mobility missiles and high-speed orbital rockets.
- **Improve flight control response and stability**
  The tail weight can adjust the local moment of inertia to improve the flight stability of the tail. In the automatic control system, this helps to suppress the nonlinear response of the tail caused by disturbances and avoid excessive corrections that cause flight path drift.
- **Structural integration and integrated design**
  Modern missile structures tend to be lightweight and integrated. Tungsten alloy counterweights are usually designed in coordination with carbon fiber composite tail fin structures and integrated in an embedded, nested or glued manner to reduce screws, welding and other connectors, improve reliability and reduce maintenance complexity.
- **The aerodynamic optimization design**
  of the counterweight layout needs to be combined with CFD (computational fluid dynamics) analysis to ensure that it does not destroy the lift distribution of the tail wing or cause vortex interference, thereby maintaining good flight aerodynamic efficiency.

5.3.4 Application Case Analysis

Tungsten alloy tail weight technology has been widely used in many types of rockets and missile systems. The following are two typical cases:

- **Optimization of the tail weight system of air-to-ground missiles**
  A certain type of air-to-ground precision-guided missile uses a folding composite tail fin, with a small tungsten alloy counterweight block arranged near the tail hinge. By improving the stability and response speed of the tail fin after folding and unfolding, the missile's terminal flight attitude is more stable. Actual measurement data shows that the hit accuracy is improved by 10% and the anti-interference ability is enhanced by 25%.
- **Small Satellite Launch Vehicle Stability Control Design**
  A light orbital launch vehicle uses customized tungsten alloy strips on both sides of the tail fin, which are embedded in the composite wing structure through structural nesting design

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to adjust the pitch and yaw stability of the aircraft. This design effectively reduces the oscillation yaw problem in the early stage of launch and makes the launch trajectory closer to the theoretical curve.

5.3.5 Future Development Trends

With the development of hypersonic weapons and intelligent precision strike platforms, the technology of tail weight systems is also evolving, and the following trends may emerge in the future:

- **Micro intelligent counterweight and dynamic response technology**
  Future tail wings may adopt a micro variable counterweight system based on MEMS structure, combined with servo controller and intelligent algorithm to achieve fine-tuning of mass distribution during flight to adapt to different flight phases and aerodynamic environments.
- **on the functional integration development of tungsten-based composite materials** combines tungsten alloy with lightweight materials such as carbon fiber and ceramic matrix to manufacture a composite tail wing that has counterweight, structural support and thermal protection functions, thereby improving the overall weight utilization efficiency.
- **The low radar visible counterweight design**
  is aimed at stealth missiles and low detectable aircraft. The counterweight design needs to take into account the electromagnetic wave reflection characteristics and minimize the RCS (radar cross section) through material coating and shape optimization.
- **The additively manufactured integrated tail wing structure**
  uses 3D printing technology to simultaneously print the tungsten alloy counterweight module and the tail wing frame, forming it into one piece and seamlessly integrating it, which shortens the production cycle, increases design freedom, and provides more space for complex aerodynamic optimization.

5.4 Aircraft Vibration Control and Reaction Mass

As the performance of modern aircraft continues to improve, the demand for lightweight structures and high-speed flight has caused aircraft to face more complex vibration problems during operation. Whether it is a jet airliner, drone, missile, or satellite, it will be affected by factors such as engine operation, structural resonance, aerodynamic disturbances, and changes in operating loads during flight, causing vibration. In order to ensure the structural integrity of the aircraft, the stability of the flight control system , and the safety and comfort of personnel and equipment, effective vibration control strategies must be adopted. Among them, the reaction mass block technology, as a passive or semi-active vibration reduction method, is playing an increasingly important role in aircraft vibration control systems.

Tungsten alloy, with its ultra-high density, excellent mechanical and thermal stability, has become the preferred material for manufacturing reaction mass blocks. Its compact mass configuration capability, fatigue resistance and corrosion resistance enable it to achieve long-lasting and effective vibration suppression in extreme flight environments.

5.4.1 Overview of Aircraft Vibration Problems

The vibration problems encountered by aircraft during flight are complex and diverse, and the main sources include:

- **Engine operation** : High-speed rotating components such as turbines, compressors and propeller shafts will cause periodic mechanical vibrations, which are especially noticeable during takeoff acceleration and thrust change stages.
- **Aerodynamic disturbance** : During high-speed flight, the unstable excitation of airflow on the wings, tail and other external structures may induce structural resonance.
- **Structural self-excited vibration** : Under certain operating conditions, coupled vibrations may occur between the internal equipment and components of the aircraft, thereby causing the vibration of the entire aircraft to expand.
- **Operational load changes** : Rapid overload changes caused by pilot control, attitude adjustment or maneuvering flight will cause instantaneous dynamic response of the structure.

If these vibrations are not effectively controlled, they may lead to the following consequences:

- Accelerated structural fatigue shortens the life of key components;
- Increased navigation and attitude control errors;
- The measurement accuracy of the instrument decreases and the data is distorted;
- Reduced comfort for cockpit personnel;
- In some cases, it may cause system instability and affect flight safety.

Therefore, vibration reduction technology has become one of the key areas of common concern for structural engineering, power systems, and electronic systems in aircraft design.

5.4.2 Mechanism of the reaction mass

The reaction mass is a vibration-reducing structural element that works on the principle of a "mass-spring-damper" system. The core idea is:

By using a group of blocks of specific mass, when the system vibrates, a reaction force in the opposite direction to the main structure is generated through inertia, thereby offsetting part or all of the vibration energy.

Reaction mass blocks can be divided into the following types according to their structural form and control method:

- **Passive type** : Utilizes natural frequency matching and designs its resonant frequency to be close to the structural vibration frequency to achieve the purpose of vibration reduction.
- **Semi-active/tuned mass damper (TMD)** : Improves adaptability by adjusting the response amplitude through damping materials or control media.

- **Active Vibration Control** : Combines electromagnetic or hydraulic devices for real-time response adjustment, but is rarely used in the aerospace field.

tungsten alloy can concentrate mass in a very small volume, making the reaction force larger and the frequency response more concentrated, which is especially suitable for aircraft scenarios with compact space and clear vibration frequency. For example, in satellite platforms or missile attitude control cabins, where the volume is strictly restricted, tungsten alloy reaction blocks can effectively replace large spring systems to achieve compact and efficient vibration reduction design.

Design requirements for tungsten alloy reaction mass

tungsten alloy reaction mass depends on the accuracy of its structural design and the stability of material properties. The main design requirements are as follows:

- **High-density and high-strength material selection:**
  Tungsten alloy has a density of up to 18.5 g/cm³, which is much higher than that of metal materials such as steel and copper in the same volume, and can achieve the maximum reaction force output per unit space. Its high tensile and compressive strength ensures that it will not deform or break in a high dynamic load environment.
- **precise mass and position design**
  depends on the precise matching of the target frequency. The mass, distribution position and installation angle of the tungsten alloy block need to be carefully calculated based on the aircraft structure modal analysis and dynamic simulation to avoid frequency mismatch or coupled resonance.
- **Environmental stability and service life**
  Tungsten alloy exhibits extremely strong corrosion resistance, radiation resistance and thermal stability, and is suitable for long-term operation in the atmospheric boundary layer, high altitude and low temperature or low-Earth orbit, ensuring that the performance of the counterweight does not decrease due to oxidation and fatigue.
- **Adjustability and modular structure**
  In changing missions and complex flight control scenarios , the design of tungsten alloy counterweight modules with adjustable structures can achieve rapid on-site tuning by changing the position or number of mass blocks, improving maintenance and adaptability.

5.4.4 Application Examples

Tungsten alloy reaction mass has been verified in multiple aircraft platforms. The main application scenarios include:

- **Turbine engine vibration control**
  In a certain type of military turbine engine, the tungsten alloy reaction block is arranged at the edge of the blade disk and behind the main shaft, and the inertial force interferes with the rotational imbalance of the main structure to suppress the structural vibration of a

specific frequency. The measured data shows that the blade amplitude is reduced by about 40% and the engine life is increased by more than 20%.

- **Satellite attitude stabilization and attitude control system vibration reduction**
  In small communication satellite platforms, tungsten alloy reaction wheels are embedded in the satellite attitude control system to generate controllable angular momentum. At the same time, the internal vibration reduction structure buffers the micro-vibration caused by the start-up of the reaction wheel , effectively reducing attitude adjustment errors and improving observation and communication accuracy.
- **Vibration suppression during missile flight**
  A certain type of air-launched missile experiences intense vibrations due to supersonic flight, and early versions have terminal yaw instability problems. By placing a tungsten alloy reaction mass block in the middle of the missile body and combining it with viscoelastic damping materials, vertical and radial vibrations are significantly suppressed, and the hit accuracy is improved by 12%.
- In the high Mach number flight test of the **hypersonic verification aircraft vibration suppression system , the tungsten alloy reaction mass block cooperates with the onboard sensor to achieve real-time vibration response adjustment,**
  providing a low-noise environment for flight control data collection .

5.4.5 Future Development Trends

As aircraft structures continue to develop towards lighter, thinner and more integrated, the requirements for reliability and stability continue to increase. The technology of tungsten alloy reaction mass blocks also faces new challenges and opportunities:

- **of the intelligent vibration reduction system**
  may be integrated with micro sensors and MEMS control units. Combined with the flight control system , it can autonomously identify the vibration state and adjust the response frequency in real time to achieve "intelligent counterweight".
- **3D printing tungsten alloy complex structure**
  additive manufacturing technology allows tungsten alloy to be processed into hollow structures, special-shaped shells or new counterweights with integrated heat conduction channels, further improving functional density.
- **The collaborative design of lightweight composite structure and tungsten alloy**
  embeds tungsten alloy into carbon fiber composite materials, aluminum honeycomb and other structures to form a lightweight and high-density combined vibration reduction module, which takes into account both structural strength and counterweight effect.
- **The research and development of electromagnetic coupling reaction blocks**
  is aimed at certain navigation and space communication platforms. Tungsten-based composite reaction mass blocks with electromagnetic absorption function are developed to combine dynamic control and electromagnetic interference shielding functions.

5.5 Tungsten Alloy Inertial Weights in Defense Weapon Systems

5.5.1 Inertial Control Requirements for Defense Weapon Systems

With the rapid evolution of information and intelligent warfare, modern weapon systems have put forward unprecedented high requirements for guidance accuracy, strike response speed and environmental adaptability. Missiles, smart bombs, drones and hypersonic aircraft are increasingly relying on inertial navigation systems (INS) to achieve autonomous positioning, path planning and flight control.

The core components of the inertial navigation system include accelerometers, gyroscopes and inertial measurement units (IMUs). The stability of its operation is highly dependent on the position and mass accuracy of inertial reference components (such as inertial wheels and counterweights). In order to maintain stable operation of the system under high-speed, high-dynamic and complex battlefield conditions, the structural design, mass distribution and material selection of the inertial counterweight become key factors in determining the guidance and control performance of the weapon system.

In this context, tungsten alloy is widely used in inertial counterweight systems in weapons and equipment due to its extremely high density, mechanical strength and thermal stability. It is the basic material to ensure the long-term and efficient operation of inertial navigation systems.

5.5.2 Advantages of tungsten alloy in defense inertial weight

Tungsten alloy has become the core material in the field of inertial weight of national defense equipment due to its unique physical and chemical properties. It has the following outstanding advantages:

- **High density, achieving small-size, high-quality counterweights.**
  The density of tungsten alloy can reach 17.0~18.5 g/cm³, which is much higher than steel (about 7.8 g/cm³) and aluminum (about 2.7 g/cm³). It enables high-quality inertial loads to be achieved in a very small volume, and is especially suitable for small ammunition and micro-flight platforms with extremely limited space.
- **Excellent environmental adaptability**
  Tungsten alloy has excellent high temperature resistance, oxidation resistance and corrosion resistance. It can serve stably for a long time in extreme temperature (-50°C to +1000°C), high humidity, salt spray, radiation and other environments commonly found on the battlefield.
- **High Mechanical Strength and Impact Resistance**
  Tungsten alloy has good tensile strength and impact resistance, and can withstand severe vibration and load shock generated during high-speed flight, launch shock and explosion fluctuations.
- **Processing adaptability and structural design flexibility**
  can achieve micron-level shape control through precision powder metallurgy, CNC cutting,

electrospark machining, etc., to meet the complex geometric structure requirements of inertial components, and can be designed into modular and integrated inertial subsystem components.

5.5.3 Specific application areas

Tungsten alloy is widely used in the inertial weight of defense field, covering many key combat systems:

• Inertial Navigation System (INS) core weight assembly

Tungsten alloy is used as the mass reference body of the inertial navigation system, which increases the moment of inertia of the gyroscope or inertial wheel to improve the system response sensitivity and stability. Especially in laser gyroscopes and fiber optic gyroscopes, tungsten alloy mass blocks are used to adjust the optical path stability and angular velocity solution accuracy.

• Precision guided munitions flight control weight system

In ballistic missiles, cruise missiles and other aircraft, tungsten alloy counterweights are widely deployed in the flight control compartment to fine-tune the center of gravity of the control surface , optimize aerodynamic control, and improve attitude response speed, thereby achieving closed-loop stable control of the flight control system. Typical models such as the "Tomahawk" cruise missile and the "Hongqi" series of air defense missiles all use tungsten alloy counterweights as flight control adjustment components.

• UAV attitude control and center of gravity adjustment module

For tactical or micro-UAV platforms, attitude stability during flight is extremely critical. Tungsten alloy inertial weights are installed in the flight control center or at the bottom of the propeller to enhance the sensitivity of attitude feedback, and achieve real-time center of gravity adjustment during flight through mechanical or electromagnetic structures, thereby improving wind resistance and endurance efficiency.

• Inertial weights for artillery shells and smart bombs

Modern artillery shells, glide bombs and other guided munitions rely on inertial elements to achieve trajectory correction. Tungsten alloy small counterweights have become an indispensable part of the inertial module to ensure rotational stability and dynamic balance.

5.5.4 Future Development Trends

With the rapid development of intelligent, integrated and miniaturized weapon systems, tungsten alloy inertial weight technology also shows the following trends:

- **Miniaturization and high integration development**
  Future weapon platforms such as swarm drones and missile-borne micro-guidance modules will require miniaturization of inertial counterweights. As an ultra-high density material, tungsten alloy still has outstanding counterweight performance on the millimeter scale and will become an important component of micro-aircraft and MEMS inertial modules.
- **designed as an integrated system with the sensor**
  will be packaged together with core components such as the attitude sensor and gyroscope

to achieve a high degree of structural integration and improve the system's anti-interference and reliability.

- **The intelligent adjustable inertial counterweight system**
  realizes dynamic adjustment of the inertial counterweight mass by integrating piezoelectric materials or variable mass block structure, which can adapt to real-time control requirements during flight and improve the response speed and flexibility of the flight control system .
- **New composite material tungsten alloy develops**
  and studies tungsten-based composite materials , such as tungsten-polymer composites and tungsten-ceramic materials, to ensure that they have stronger machinability and electromagnetic compatibility while ensuring high density, and to meet the requirements of future multi-functional combat platforms.

Tungsten alloy counterweights have a wide range of critical applications in the aerospace field due to their unique high density, high strength and good environmental adaptability. From aircraft center of gravity adjustment, satellite inertial control to rocket tail counterweights and vibration suppression, to inertial counterweights for national defense weapon systems, the value of tungsten alloys is irreplaceable. With technological advances, the design and manufacturing technology of tungsten alloy counterweights will continue to upgrade, driving aerospace equipment towards higher performance and greater intelligence.

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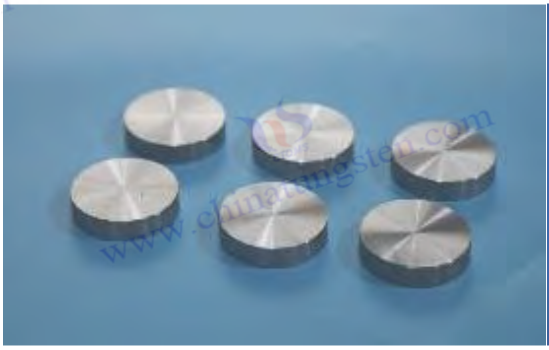
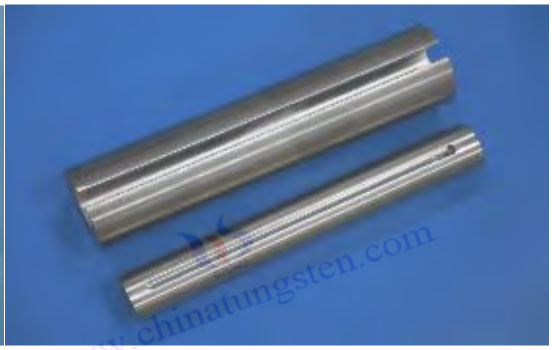

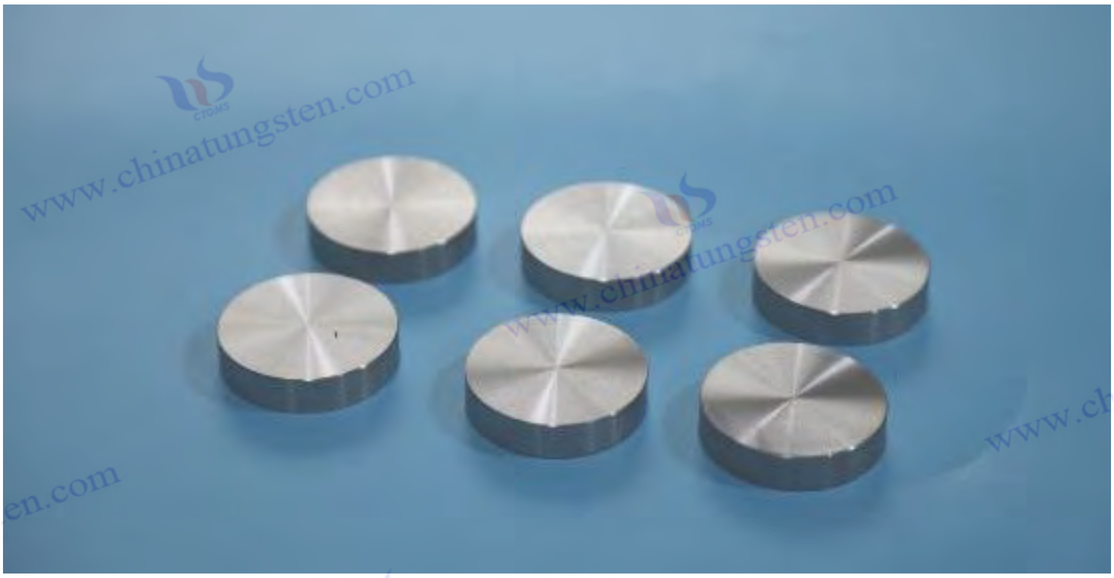

Chapter 6 Application of Tungsten Alloy Counterweights in Automobiles and Engineering Machinery

Tungsten alloy has become an important material in the design of counterweights in the automotive and engineering machinery fields due to its high density, high strength, and excellent wear and corrosion resistance. The reasonable design of counterweights not only improves the stability, power transmission efficiency, and safety performance of vehicles or machinery, but also significantly optimizes the control experience and mechanical performance. With the increasingly significant trend of lightweight and high performance of automobiles, and the development of engineering machinery towards large-scale and intelligent, the application value of tungsten alloy counterweights continues to increase. This chapter will detail the application practice and technical development of tungsten alloy counterweights in the dynamic balance of automobile engines and chassis, the optimization of F1 racing counterweights, high-speed rail and high-speed train counterweight modules, crane and shield machine counterweights, and stable counterweights for large-scale civil construction equipment.

6.1 Dynamic weight balance between automobile engine and chassis

tungsten alloy plays a vital role in the power system and chassis structure of modern automobiles, especially in improving the dynamic balance of mechanical systems, suppressing vibrations, and improving the stability and comfort of the entire vehicle. This section comprehensively explains the application of tungsten alloy counterweights in automobile engines and chassis systems, covering technical background, material advantages, design methods, typical cases and future development directions.

6.1.1 Technical Background of Automobile Engine Counterweight

As the power core of the car, the engine contains multiple high-speed rotating and reciprocating parts, such as the crankshaft, flywheel, piston connecting rod system, etc. These parts will generate large centrifugal force and inertial impact during operation due to uneven mass or mechanical structure deviation. If not controlled, it is very easy to cause:

- The vibration of the whole vehicle intensifies and the driving comfort decreases;
- The fatigue of parts increases, causing early wear or breakage;
- Fuel efficiency decreases and engine energy consumption increases.

To this end, modern engine designs generally introduce **dynamic counterweight systems** , which balance the dynamic unevenness of the rotor system by adding high-density small counterweights at key moving parts to achieve stable operation at high speeds.

Traditional counterweight materials such as cast iron or steel can no longer meet the needs of lightweight and high-performance development of the new generation of automobiles in terms of density, volume, and thermal stability. Therefore, **tungsten alloy, due to its excellent physical and mechanical properties, has gradually replaced traditional materials and become the preferred counterweight solution** .

6.1.2 Advantages of Tungsten Alloy Counterweights in Engines

tungsten alloy in automobile engine counterweights are mainly reflected in the following aspects:

- **High density enables small size and high quality counterweights.**
  The density of tungsten alloy is as high as 17.0-18.5 g/cm³, which is almost twice that of steel. With the same mass, it takes up less space, allowing the accurate placement of counterweights in space-constrained areas (such as crankshafts or rotor ends), improving dynamic balancing accuracy and effectively supporting the compact design of engines.
- **Excellent high temperature performance**
  Gasoline or diesel engines are in high temperature combustion environment all year round. The melting point of tungsten alloy is as high as 3410°C. Even when the engine is running at a working temperature of 250-500°C for a long time, it can still maintain stable shape and mechanical properties.
- **Corrosion and wear resistance**
  Tungsten alloy has strong resistance to chemical corrosion and can be used for a long time in an environment containing oil, combustion byproducts, and even acid and alkali residues. Its high hardness also makes it less likely to wear in long-term friction, reducing maintenance frequency.
- High-density tungsten alloy **with strong vibration suppression ability**
  has excellent inertial response characteristics, which can effectively absorb high-frequency micro-vibration, reduce the noise and unbalanced impact of the whole machine, and is a key material for engine NVH (noise, vibration and acoustic comfort) engineering.

6.1.3 Key points of dynamic counterweight design

Dynamic weight distribution in automobile engines and chassis systems involves the optimization of multiple key components. Common design solutions include:

- **Crankshaft counterweight design**
  When the crankshaft rotates unbalanced, it will cause severe vibration. Tungsten alloy counterweights are usually precisely embedded in the two ends or waist of the crankshaft through forging or sintering, and compensate for mass offset through three-dimensional center of gravity adjustment. Compared with steel, tungsten counterweights are small in size and flexible in arrangement, and can achieve sub-gram inertia compensation.
- **flywheel**
  also needs to accurately control the engine's rotational inertia. The integrated design of the tungsten alloy counterweight and flywheel can achieve sensitive inertia adjustment and response time control by changing its embedding depth and annular distribution.
- **Engine suspension system dynamic balancing weights For vehicles equipped with small three-cylinder engines or electric drive systems,**
  tungsten alloy micro-balance weights are also used in the engine suspension structure to adjust the overall system resonance frequency and prevent idle vibration from propagating to the vehicle body.
- **Chassis counterweight and suspension stabilizer block**
  In the vehicle chassis structure, such as subframe, shock absorber tower top or steering mechanism, by installing tungsten alloy balance block, the vehicle center of gravity adjustment and lateral stability optimization can be achieved, which is especially suitable for vehicles with high requirements for high-speed driving and cornering stability.

6.1.4 Typical application cases

- **Dynamic weight balance system for luxury car engines**
  A high-end car brand's V8 turbocharged engine uses a customized tungsten alloy crankshaft balance block, combined with laser welding technology to achieve ultimate dynamic balance, allowing the engine to run stably above 7500 rpm, while significantly improving driving smoothness and quietness.
- **New energy vehicle electric drive system The electric drive system of new energy electric vehicles (such as permanent magnet synchronous motors) has higher requirements for rotor dynamic balance. A company installed**
  tungsten alloy inserts inside the drive motor, combined with dynamic monitoring feedback, to achieve flywheel-level inertia adjustment, improve acceleration response by 30%, and reduce rotor heat generation.
- **The racing engine inertia adjustment module uses a hollow**
  tungsten alloy balance ring in the F1 racing car . By changing its relative position, the

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engine inertia is adjusted to meet the personalized needs of different tracks for speed response.

6.1.5 Future Development Trends

As the electrification, intelligence and modularization of automobiles accelerate, the role of tungsten alloy counterweights in engines and chassis will continue to evolve:

- **Intelligent dynamic weight balancing system** : Combining MEMS sensors and electromagnetic actuators, a tungsten alloy dynamic weight balancing system with real-time feedback is constructed, which can automatically adjust the center of gravity and inertia according to engine speed and load changes to achieve active vibration reduction and fuel efficiency optimization.
- **Lightweight and functional integrated design** : Integrate tungsten alloy counterweight with electromagnetic shielding, thermal buffer and other functions to reduce the number of parts and improve system reliability.
- **Green manufacturing and utilization of recycled materials** : Develop low-energy tungsten alloy sintering technology and explore the recycling of scrapped engine weights to achieve circular economy and carbon neutrality goals.

6.2 Optimization Design of Weight Distribution of F1 Racing Car

As one of the most technically demanding racing categories in the world, the performance optimization of F1 racing not only depends on the power system and aerodynamic design, but also highly depends on the scientific design and layout of **the vehicle weight system .** Tungsten alloy, with its extremely high specific gravity and stable physical properties, has become an ideal material for F1 teams in dynamic balance adjustment, center of gravity layout optimization, and track adaptability fine-tuning.

6.2.1 Importance of weight in F1 racing

In F1 racing, every gram of weight distribution can determine victory or defeat. According to FIA regulations, the minimum total mass of the 2024 F1 car is 798 kg (including the driver), which means that the design team must make extreme adjustments to **the center of gravity, height, left-right balance and dynamic load inertia of the car body under strict weight restrictions** .

The counterweight is not only used to fill the excess in the vehicle structure, but also needs to accurately coordinate with the working conditions of **the aerodynamic components, suspension system, and braking system** to achieve the following purposes:

- **Optimize cornering performance** : Precise front and rear weight distribution can improve steering response and reduce understeer or oversteer;
- **Improve braking efficiency** : weight distribution affects tire ground pressure, thus affecting braking performance;

- **Improved acceleration and cornering traction** : Shifting the center of gravity backward helps improve drive wheel traction;
- **Improved car handling consistency** : Weight adjustment can improve the driver's confidence and sense of control over the vehicle, especially in slippery, bumpy or variable temperature track conditions.

6.2.2 Advantages of Tungsten Alloy Counterweights in F1 Racing

The body structure of F1 racing cars is extremely compact. Traditional materials such as steel and aluminum cannot provide the required mass in the limited space. Tungsten alloy has become the only choice for high-end counterweight materials due to its excellent performance.

- **High mass concentration:**
  The density of tungsten alloy is as high as 18.5 g/cm³, which is more than 2.3 times that of steel. The volume of the counterweight of the same mass is significantly smaller, allowing designers to place it in extremely narrow spaces, such as the center of the floor, behind the wheel arch, or in the dead corner of the car body, to achieve precise mass allocation.
- **Excellent thermal stability and structural stability.**
  The temperature of the brake disc in F1 events can reach up to 1000°C, and the temperature difference inside the car body can exceed 50°C. Tungsten alloy has good thermal inertia and dimensional stability. It can withstand high temperature shock for a long time without expansion, deformation or fatigue, ensuring the long-term consistency of the weight effect.
- **High machinability and customization flexibility**
  Tungsten alloy can be made into complex geometric shapes through precision CNC machining, EDM electric spark and MIM injection molding, etc., to adapt to the structure of different parts of the car body. It has high strength and good wear resistance, and can be combined with common F1 materials such as carbon fiber and titanium alloy to improve integration and reliability.

6.2.3 Weight distribution optimization strategy

Tungsten alloy counterweights are not just "filling in the blanks" in racing cars. Their layout design itself is a highly complex system engineering, which often requires dual-track optimization of simulation + actual measurement.

- **weight distribution**
  ratio of about 40:60, but the specific ratio can be flexibly adjusted due to track characteristics (such as many hairpins or long straight lines). The small size and high quality of tungsten alloys allow designers to fine-tune the weight distribution within the front nose or rear wing structure to improve the vehicle's directional stability during braking and its ability to accelerate out of corners.
- **Lateral weight adjustment**
  The left and right weights play a decisive role in the lateral load distribution of the vehicle

when turning. Especially on street circuits such as Monaco and the narrow Silverstone Circuit, a reasonable lateral weight difference can significantly improve the cornering response and reduce steering drift.

- The lower the center of **gravity , the more stable the car.**
  Tungsten alloy blocks are often installed at the lowest point of the car body (such as the front and rear ends of the chassis, below the battery), to help the whole car get stronger downforce when driving at high speed, so that the vehicle can maintain absolute ground contact when accelerating downhill or changing lanes at high speed.

6.2.4 Actual design and manufacturing

- All tungsten alloy counterweights are processed by **CNC**
  five -axis machine tools with a control accuracy of better than ±5 μm , ensuring that the weight error of each piece is less than 0.05%. After manufacturing, the size and quality are verified by the CMM three-coordinate measurement system.
- The connection between the counterweight and the body frame of **the structural integrated fixed design must be lightweight and high-strength, and is usually fixed by titanium alloy threaded holes and carbon fiber bracket nesting. Some teams even use 3D printing clamping systems to achieve efficient assembly and quick replacement without welding.**

- **Data-driven dynamic adjustment system**
  Each F1 car is equipped with a large number of sensors to collect data including longitudinal acceleration, lateral load, tire temperature and ground contact. Engineers use simulation analysis (such as finite element analysis FEA + multi-body dynamics MBD) to customize tungsten weight solutions for different tracks before the race, and can also quickly adjust between qualifying and the race.

6.2.5 Case Analysis

- **Cornering performance improvement application A top F1 team introduced a new** tungsten alloy centralized weight module (located on the rear floor) in the Monza circuit in Italy . Compared with the traditional module, the volume is reduced by an average of 18%, and the center of gravity is moved back by 2.5 mm without increasing the total mass. Ultimately, it helps the vehicle's cornering speed increase by 1.3 km/h and the cornering time is shortened by 0.21 seconds.
- **of the 2023 Monaco Grand Prix , another team specially customized a tungsten alloy "anti-roll block" for the rainwater drainage design on the left side of the vehicle, so that the vehicle can maintain directional stability in**
  low-grip corners, significantly reduce the number of tail slides, and finally win a place in the points zone.

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6.3 High-speed rail and high-speed train counterweight module

As modern rail transit places higher demands on operating speed, comfort and safety, the structural design of high-speed trains is becoming more complex and sophisticated. Under the premise of highly integrated body structure, limited weight and variable operating conditions, the reasonable arrangement of **high-performance counterweight modules** has become an indispensable part of train engineering design.

Tungsten alloy is gradually replacing traditional materials such as steel and lead due to its high density, high strength and excellent durability. It is used in high-speed railways and high-speed trains in the fields of **center of gravity control, dynamic load vibration reduction and noise control** , and its engineering value is becoming increasingly prominent.

6.3.1 High-speed rail counterweight technology background

When running at a speed of 300-400 km/h, high-speed trains will face complex physical conditions such as strong **vibration loads, centrifugal force, wind resistance disturbance, braking shock** , etc. The dynamic response of the car body is even more intense when turning, accelerating or decelerating, or passing through heterogeneous sections such as bridges and tunnels.

center of gravity adjustment and vibration control mechanisms at the early stage of design . The counterweight module, as a system-level dynamic balancing and vibration suppression component , mainly undertakes the following tasks:

- **Correct the center of gravity of the vehicle and carriage** , and optimize the wheel axle load distribution;
- **Adjust the matching degree of component vibration frequency** to prevent resonance and structural fatigue;
- **Improve ride comfort and noise levels** , and enhance the quality of commercial operations;
- **Supports the suspension system to achieve precise dynamic response** and reduce system complexity.

6.3.2 Advantages of Tungsten Alloy Counterweight Module

In the rail vehicle industry, the counterweight module must not only be "heavy" but also "stable". Tungsten alloy materials have many characteristics, which give them irreplaceable technical advantages in high-speed rail applications:

- **high-density and high-quality**
  tungsten alloy counterweight can reach 18.0-18.5 g/cm³, which is more than twice that of ordinary carbon steel. In the bottom of the vehicle body or the suspension cavity where space is extremely limited, the required counterweight can be achieved in a smaller volume, avoiding sacrificing other system layouts.

- **Excellent mechanical strength and dynamic load adaptability.**
  The high-speed rail body is subjected to millions of vibration cycles during operation. Tungsten alloy has high tensile strength, high Young's modulus and extremely low fatigue crack growth rate, ensuring that the counterweight module remains structurally intact under long-term high-frequency loads.
- **Excellent environmental resistance:**
  China's high-speed rail lines span across various climate zones such as plateaus, deserts, and coastal areas. Tungsten alloy has excellent resistance to moisture, heat, salt spray, acid and alkali corrosion, and can serve in extreme climate conditions for a long time without rusting or deformation.
- **Good structural processability**
  can realize complex and special-shaped structure design through powder metallurgy, hot isostatic pressing, CNC processing and welding forming, meeting the needs of modular installation, rapid replacement and precise integration of high-speed trains.

6.3.3 Counterweight module design

In the high-speed rail vehicle system, the layout of tungsten alloy counterweights needs to be designed in coordination with the vehicle structure, electronic control system, suspension system, and noise and vibration control strategy. The main design directions include:

- **The body chassis counterweight**
  is usually installed on a structural bracket or low-level cabin near the center axis of the body. By accurately adjusting the longitudinal and lateral center of gravity positions, it controls the train's tendency to overturn, sway and shake when running at high speed.
- **counterweight module of suspension system**
  can be used in primary or secondary suspension system to reduce vibration transmission rate, improve vehicle stability and vibration isolation effect by adjusting system resonance frequency and improving shock absorber response.
- **Wheel and bogie counterweights are equipped with**
  tungsten alloy blocks at specific positions of the wheel axle system or bogie for **inertia balance** and noise suppression, especially in curve sections or turnout passages, to suppress lateral vibration and serpentine motion and extend wheel-rail life.
- **The vehicle equipment counterweight auxiliary structure**
  performs local counterweighting on large-mass equipment such as air-conditioning units and traction motors to avoid asymmetric vibrations. It also performs balance adjustments on modules such as on-board batteries and electronic control boxes to improve EMC stability and ease of maintenance.

6.3.4 Application Practice

In recent years, high-speed train manufacturers in many countries have begun to introduce tungsten alloy counterweight systems in the vehicle commissioning and optimization process, and have achieved remarkable results:

- **Case 1 : CR400AF high-speed train engineering test**
  A certain type of EMU adopts tungsten alloy chassis centralized weight module. Compared with the traditional cast iron solution, the structural volume is reduced by nearly 50%, while the train operation stability index is improved by 11%, and the pass rate of crosswind stability test is increased by 15%.
- **Case 2: A high-speed train comfort improvement project in Europe introduced modular**
  tungsten counterweights in the secondary suspension system , which effectively improved the cabin shaking problem. The RMS value of seat acceleration decreased by about 0.08 m/s^2, and the score in the passenger satisfaction survey increased by more than 20%.

6.3.5 Development Trend

With the advancement of the goals of "intelligent high-speed rail", "green high-speed train" and "carbon peak and carbon neutrality", the design of tungsten alloy counterweight modules is gradually moving towards digitalization, intelligence and sustainability :

- In the future, the counterweight blocks of the **intelligent adjustable counterweight system will be combined with**
  MEMS sensors and **electric displacement modules to achieve real-time mass adjustment and center of gravity migration** as the vehicle load and running speed change , thereby improving the system's adaptability and energy saving level.
- **Material recycling and green manufacturing**
  promote **the recycling metallurgical technology** and **powder recycling system of** tungsten alloys , reduce dependence on tungsten resource mining, and realize the closed-loop utilization of high-end counterweight materials.
- **The integrated multifunctional modular design**
  combines the functional requirements of heat insulation, sound absorption, flame retardancy, vibration reduction, etc., and integrates the tungsten alloy counterweight structure with other components (such as cable troughs and structural reinforcements) to improve the space utilization rate and structural simplification level of the train.

6.4 Cranes, lifting equipment and shield machine counterweights

In modern large-scale engineering construction and infrastructure construction, heavy engineering machinery such as cranes, hoisting equipment and shield machines undertake key tasks. These equipment generally have problems such as center of gravity offset, structural shaking and load imbalance during operation. If the counterweight system is not effectively configured, it will not only cause unstable mechanical operation and reduce construction efficiency, but also may cause safety accidents. Tungsten alloy counterweight blocks have become an ideal choice for high-performance counterweight solutions in the above equipment due to their high density, high strength and excellent structural stability.

6.4.1 Importance of counterweights for construction machinery

When construction machinery performs actions such as lifting, excavating, rotating or transferring, its center of gravity will shift as the structure and load change. For example:

- After **the crane lifts the heavy object, the overall center of gravity moves forward, which is very likely to cause the risk of overturning;**
- During the advancement **of the shield machine , the center of gravity needs to be constantly adjusted to maintain the balance of front and rear forces and ensure the direction of excavation;**
- **Large lifting equipment** needs to maintain the stability of the slewing platform under asymmetric load conditions to avoid foundation settlement or structural vibration.

Therefore, scientifically and rationally designing the counterweight system to ensure that the machine has sufficient stability under various working conditions is a core engineering issue to ensure construction safety, machine life and operating efficiency.

6.4.2 Application Advantages of Tungsten Alloy Counterweights

Compared with traditional steel or cast iron counterweights, tungsten alloy has the following significant advantages, making it more suitable for high-performance counterweights in modern engineering machinery:

- **High density reduces the volume of counterweights.**
  The density of tungsten alloy is as high as 18 g/cm³, which is much higher than that of ordinary steel (about 7.8 g/cm³). It can achieve higher counterweight mass in a limited space, greatly reduce the volume of the module, and meet the requirements of compact structure design.
- **Excellent wear and corrosion resistance**
  Engineering equipment is often exposed to extreme environments such as high temperature, high humidity, high salt, acid, alkali or sand and dust . Tungsten alloy itself has good chemical stability and physical wear resistance, which ensures its long-term service stability and reduces the frequency of replacement.
- **Strong impact resistance**
  Tungsten alloy has high Young's modulus and high yield strength. When facing sudden loading of heavy objects, foundation resonance and severe collision of construction equipment, it can still maintain small deformation and high stability, effectively buffering the impact load.
- **Non-toxic and environmentally friendly alternative materials**
  The use of lead in traditional counterweights poses toxicity and environmental pollution

risks. Tungsten alloy is a non-toxic, recyclable green metal that meets the compliance requirements of current engineering projects for environmental regulations.

6.4.3 Counterweight design principles

The counterweight design of construction machinery should be customized and optimized according to its equipment structure, operation mode and working scenario, mainly following the following principles:

- **Mechanical balance is preferred.**
  Tungsten alloy counterweights should be arranged on key structures where the center of gravity changes significantly, such as the opposite side of the boom , the rear end of the rotating platform or the tail of the shield machine. The dynamic balance of the structure can be achieved by calculating the gravity moment to avoid the risk of rollover or overturning.
- **For safety reasons,**
  the connection method of the counterweight must adopt **a high-strength mechanical fastening system** , such as a combination of bolts + locating pins + limit slots, and an anti-loosening structure must be designed to prevent the counterweight from loosening or falling off during equipment vibration.
- **Easy maintenance**
  The modular design allows the counterweight to be quickly replaced and adjusted, facilitating flexible deployment under changing on-site construction conditions. Some equipment also uses a guide rail or slide design to improve the efficiency of counterweight installation.
- The future trend of **structural integration requires that**
  tungsten alloy counterweights not only have the function of bearing weights, but also can be integrated with equipment structures such as support beams and reinforcement plates to improve the overall structural rigidity and simplify the installation process.

6.4.4 Specific application examples

The following are typical application examples of tungsten alloy counterweights in construction machinery:

- **The tower crane counterweight is equipped with a**
  tungsten alloy module at the base of the tower crane or at the rear end of the slewing platform , which effectively improves the reaction force support capacity of the front load during the lifting process . Especially in the construction of high-rise buildings in cities, the lifting space is limited, and the high-density characteristics of tungsten alloy solve the problem of "too large volume" of traditional counterweights.
- In **large hoisting equipment , such as wheeled cranes and crawler cranes, tungsten alloy counterweights can be placed under the slewing chassis**
  or jib to suppress the center of gravity shift caused by the extension of the boom during the lifting process and improve the safety margin of the lifting operation.

- The tungsten alloy blocks of **the shield machine's counterweight system are installed on both sides of the shield machine's tail and behind the main drive system to compensate for the forward center of gravity of the**
  cutterhead during advancement , maintain the machine's posture stability during excavation, and reduce yaw and track interference.
- **Crawler crane luffing counterweight system**
  Some high-end crawler cranes are equipped with a movable tungsten alloy counterweight vehicle, which can adjust the counterweight position through linkage to adapt to the real-time center of gravity change requirements when the boom changes.

6.4.5 Industry Development Trends

As lifting and shield equipment develop towards **larger tonnage, longer operation cycle, and more complex working conditions** , the tungsten alloy counterweight system will show the following technical evolution trends:

- **Structural integration and efficient assembly**
  Tungsten alloy counterweights will be more integrated into the main structure of the equipment to achieve "structure + function" integration. For example, the counterweight block is integrated with the reinforcement ribs at the tail of the boom to reduce welded parts and improve structural strength.
- **The intelligent monitoring and dynamic adjustment**
  counterweight system will introduce **intelligent weighing modules, inertial sensors, position encoders** and other electronic components to achieve real-time center of gravity monitoring and counterweight status feedback, provide data support for the equipment control system, and assist in automatic adjustment of the counterweight position.
- **Green manufacturing and recycling**
  Under the background of "dual carbon" goals, construction machinery manufacturers will pay more attention to the recyclability and smelting energy consumption of counterweight materials. Tungsten alloy can be reused through recycling and re-sintering technology, which is in line with the future circular economy model.
- **The multifunctional composite counterweight design**
  integrates the counterweight block with components such as the hydraulic oil tank, battery compartment, and cooling unit to improve the compactness of the vehicle structure and the degree of functional integration.

6.5 Stable counterweight scheme for civil engineering and large construction equipment

In large-scale civil engineering projects such as modern infrastructure construction, urban expansion, and mining development, heavy construction equipment such as excavators, bulldozers, loaders, and pile drivers are widely used. When these equipment are operating under high loads, their operating stability, center of gravity control, and anti-overturning ability are directly related to construction efficiency and work safety. Especially in complex working conditions such as soft soil, slopes, irregular terrain, or extreme weather, the equipment must have excellent balance performance.

Tungsten alloy has become the core material of modern high-performance counterweight systems due to its high density, high strength and excellent environmental adaptability, providing a reliable and efficient counterweight solution for civil engineering machinery.

6.5.1 Technical Background of Counterweights for Large Construction Equipment

When civil engineering construction equipment performs tasks such as grabbing, shoveling, digging, and pushing, it will produce a large displacement of the center of gravity. For example:

- **of the excavator** is fully extended, the center of gravity of the whole machine moves forward. If the counterweight is insufficient, the tail will easily tilt or the whole machine will overturn.
- When **the loader is lifting the bucket with full load, the body of the loader shifts longitudinally, increasing the risk of overturning;**
- **the bulldozer** is performing high-speed pushing operations, it needs to maintain a low center of gravity to prevent side sliding and shaking.

To meet the above requirements, the equipment needs to be equipped with a counterweight system with sufficient quality, reasonable structure, and reliable fixation. Traditional steel or cast iron counterweights have defects such as large volume, difficult layout, and insufficient density, which are difficult to meet the requirements of modern large-scale construction equipment for compact structure and efficient operation. Tungsten alloy has gradually become the mainstream high-performance counterweight material because of its high density of 18 g/cm³ and provides greater mass in the same volume.

6.5.2 Advantages of Tungsten Alloy Counterweights

tungsten alloy in the counterweight system of civil engineering construction equipment are reflected in the following aspects:

- **High density saves installation space.**
  The specific gravity of tungsten alloy is about 2.3 times that of traditional steel, so that the required counterweight mass can be obtained in a very small volume, which is very suitable for the tail, bottom or bearing area of equipment with compact installation space.
- **Strong durability, adaptable to harsh working conditions**
  Civil construction sites are often accompanied by dust, moisture, acid and alkali corrosion, high humidity and high temperature and other complex environments. Tungsten alloy itself has excellent corrosion resistance and wear resistance, which significantly extends the service life of the counterweight and reduces the frequency of replacement and maintenance.
- **Excellent impact resistance**
  Under high dynamic loads, construction equipment is subject to frequent impact and

vibration. Tungsten alloy has high Young's modulus and yield strength, which can effectively resist fatigue damage and ensure the stability of the counterweight structure and working reliability.

- **Non-toxic and environmentally friendly, replacing lead- based materials**
  . Compared with some traditional lead-containing counterweight materials, tungsten alloy is non-toxic and contains no volatile heavy metals. It can fully meet the requirements of international environmental regulations such as REACH and RoHS, and is widely used in civil and engineering machinery fields.

6.5.3 Counterweight design

tungsten alloy counterweights in large-scale construction equipment requires a scientific and reasonable modular layout plan based on the equipment structure, working posture and construction environment:

- **low center of gravity design**
  should be installed on the equipment chassis or the rear of the vehicle body as much as possible to keep the center of gravity of the whole machine at a low position and enhance the anti-overturning ability. It is especially suitable for working conditions with large lateral thrust such as bulldozers and pile drivers.
- **The counterweight**
  block is designed as several replaceable and stackable modular units. Different modules are connected by bolts, latches or rails to adjust the counterweight mass and center of gravity as needed. It is quick to replace on site and adapt to different construction tasks.
- **Safety fixing measures:**
  The counterweight block needs to be fixed by a high-strength mechanical structure and equipped with protective devices such as anti-loosening nuts, anti-slip gaskets, and limit structures to prevent the counterweight from loosening and falling off during construction and improve operation safety.
- **Integrated with structure design**
  During the equipment design stage, the tungsten alloy counterweight can be embedded into the main structure of the equipment (such as the tail frame, side panels, shields, etc.) to achieve the integration of structure and counterweight, saving installation space and improving the rigidity of the whole machine.

6.5.4 Typical application examples

The following are typical application scenarios of tungsten alloy counterweights in specific equipment:

- **Large excavator counterweight system**
  The tungsten alloy counterweight module is installed at the tail of the excavator to achieve mass balance in a limited space and improve the stable response of the whole machine to

the movement of the heavy arm. When operating in some plateaus or geologically weak areas , the counterweight is specially treated with anti-impact to prevent cracking.

- **loading**
  operation, the tungsten alloy block is installed between the rear of the vehicle and the chassis. By adjusting its mass and layout, the turning radius of the whole machine and the balance of bucket lifting and lowering can be optimized, thus improving operational flexibility and efficiency.
- Tungsten alloy is used in the design of the bottom frame and tail balance beam of the bulldozer **counterweight optimization system**
  , so that the equipment can maintain strong anti-rollover ability during high-speed propulsion and sharp turns, and adapt to complex soil construction.
- **The counterweight of pile foundation driving equipment**
  utilizes the high density of tungsten alloy to add symmetrical counterweights to the main tower or below the equipment, effectively offsetting the disturbance of the center of gravity of the machine body caused by the impact of the hammer head and improving the vertical control ability of the pile position.

6.5.5 Future Technology Trends

In the future, with the development of intelligent construction technology, high-end engineering machinery and equipment, and digital construction, the tungsten alloy counterweight system will evolve in the following directions:

- **The intelligent counterweight adjustment system**
  combines an inertial measurement unit (IMU), a laser rangefinder, a pressure sensor, etc. to sense changes in the center of gravity of the equipment in real time, and drives the tungsten alloy module to move through a motor to achieve adaptive counterweight adjustment.
- **Composite design of counterweight and energy system**
  In electric excavators, hybrid bulldozers and other equipment, tungsten alloy counterweight can also serve as **battery protection compartment and cooler protective armor** , realizing multiple integration of weight, structure and function.
- **Green manufacturing and recyclable system construction**
  With the advancement of the dual carbon policy , the production of tungsten alloy weights will transform towards low-carbon and energy-saving, increase the recycling rate of waste weights, and build a closed-loop system of circular economy.
- **Additive Manufacturing and Complex Structure Customization**
  Customize complex structure tungsten alloy counterweights through 3D printing technology to further optimize the structural distribution and weight layout, and adapt to the future trend of personalized and small-batch customization of construction equipment.

Chapter Summary

Tungsten alloy counterweights are widely used and critical in the fields of automobiles and engineering machinery, covering dynamic counterweights for engines and chassis, distribution of counterweights for racing cars, counterweight modules for high-speed railways, counterweights for lifting machinery, and stable counterweights for large construction equipment. With its excellent high density and mechanical properties, tungsten alloys have greatly promoted the lightweight, high performance, and safety of vehicles and machinery. With the development of intelligent manufacturing and material technology, the design of tungsten alloy counterweights will evolve towards higher precision, modularization, and intelligence, pushing the automotive and engineering machinery industries towards a higher level of technological innovation.

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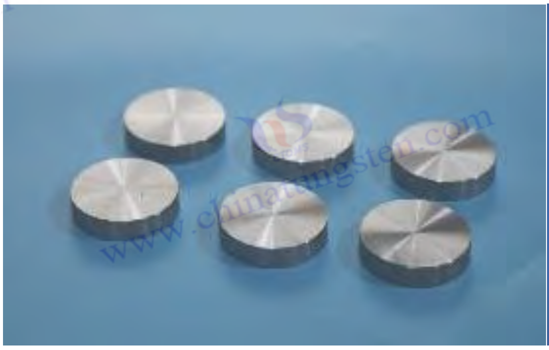
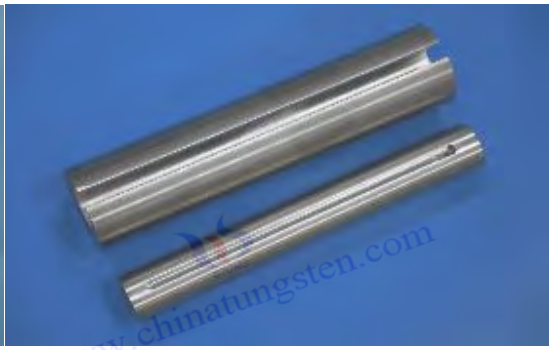

Chapter 7 Application of Tungsten Alloy Counterweights in Electronic and Medical Equipment

7.1 Counterweight components for precision instruments and gyroscopes

In the field of high-precision instruments, especially in inertial navigation systems, counterweight components play a key role in mass balance. As an important component of inertial navigation systems, the mass distribution of the rotor and rotating parts of gyroscopes is directly related to the measurement accuracy and system stability. Tungsten alloy, with its excellent high density and mechanical properties, has an irreplaceable advantage in this type of counterweight components.

7.1.1 Case Analysis

Aviation inertial navigation gyro counterweight

A well-known aerospace company uses tungsten alloy micro-weights to precisely balance the gyro rotor for its new generation of inertial navigation gyroscopes. With a density of up to 18.5 g/cm³, the tungsten alloy counterweights achieve microgram-level mass accuracy in a very small space. This design significantly reduces the vibration and eccentric force of the rotor caused by uneven mass distribution, suppressing the error source in the measurement process.

After system dynamic simulation and rigorous dynamic balance testing, the precise arrangement of the counterweights has improved the gyroscope's measurement accuracy of angular velocity and further optimized the performance of the aircraft's attitude control system. This has effectively improved the stability and safety of the aircraft's navigation, especially in high-dynamic environments.

High-precision counterweights in geological exploration equipment In the field of seismic exploration, the stability of vibration sensors and seismic instruments determines the accuracy of geological data. A geological exploration

equipment manufacturer uses counterweight elements made of tungsten alloy and installs them in the vibration system of the equipment to ensure that the sensor has a high sensitivity response to tiny ground vibrations.

tungsten alloy components ensures that the counterweight block has sufficient mass under limited volume, enhancing the mechanical stability and anti-interference ability of the equipment. In complex field environments, the instrument can still maintain stable performance, and the accuracy of data collection is significantly improved, effectively supporting geological structure analysis and resource exploration.

7.1.2 Material Process

Powder Metallurgy Process

Tungsten alloy weight components are usually prepared using advanced powder metallurgy technology. High-purity tungsten powder is used as the raw material, and a highly dense tungsten alloy blank is formed through high-temperature sintering under vacuum or inert atmosphere protection. This process eliminates pores and inclusions, ensuring that the internal structure of the material is uniform and dense.

The sintered tungsten alloy material has excellent mechanical strength and stable physical properties, which can adapt to the long-term working environment of precision instruments. The powder metallurgy process can also optimize the hardness, toughness and processing performance of the material by adjusting the composition ratio (such as adding flux such as nickel and iron) to meet the special requirements of different instruments for counterweight materials.

Machining and precision grinding

The tungsten alloy sintered block is machined to form the basis of the counterweight element. Rough and fine machining are performed using CNC machine tools, combined with ultra-precision grinding technology to achieve micron-level dimensional accuracy. The grinding process pays special attention to surface flatness and dimensional consistency to ensure that the counterweight block can meet the design requirements during assembly.

During the machining process, heat input and cutting parameters must be strictly controlled to prevent local stress and deformation of the material. For ultra-small counterweight components, micro-machining technologies such as electrical discharge machining (EDM) can also be used to achieve precision manufacturing of complex shapes.

Surface treatment

In order to improve the corrosion resistance and surface finish of the counterweight components, chemical polishing, mechanical polishing and metal plating processes are often used. Chemical polishing can remove surface microscopic defects, reduce the friction coefficient, and reduce the risk of particle shedding.

Surface plating (such as nickel plating, gold plating, etc.) not only improves corrosion resistance, but also improves the assembly performance of components and prevents dimensional changes and poor contact caused by oxidation. For specific applications, tungsten alloy surfaces are also coated with radiation or anti-wear coatings to enhance their environmental adaptability.

7.1.3 Design Method

Mass distribution simulation analysis

During the design phase, finite element analysis (FEA) was used to simulate the dynamic behavior of the gyroscope rotor, focusing on the impact of mass distribution on the rotor's rotational stability. By simulating different weighting schemes, the optimal position, shape and mass of the weight block were determined to achieve an ideal balance of the rotor inertia.

The simulation process combines the rotor vibration mode to predict the possible resonance frequency and amplitude, avoids nonlinear vibration and dynamic instability in the system, and improves the overall equipment reliability.

Dynamic balance test

After actual manufacturing, the rotor with the weight elements assembled is tested using a high-precision dynamic balancing machine. The direction and magnitude of the deviation are determined by measuring the unbalanced force and vibration amplitude during the rotor rotation.

The test data is fed back to the design team to guide the fine-tuning or increase or decrease of the counterweight to ensure that the whole machine rotates smoothly and meets the design specifications. This process is iterated many times until the predetermined microgram-level balance accuracy is achieved.

Fault-tolerant design

Taking into account the errors in the manufacturing and assembly processes, the design reserves a balance for counterweight adjustment so that the mass and position of the counterweight block can be adjusted within a small range to compensate for processing tolerances and assembly errors.

The fault-tolerant design also includes the interchangeability of the counterweight modules to facilitate on-site maintenance and adjustment, ensuring the stability and reliability of the instrument in long-term use.

7.2 Tungsten Block for Anti-Shake in Mobile Phone Camera Module (OIS)

With the continuous improvement of smartphone camera functions, Optical Image Stabilization (OIS) has become one of the key technologies to ensure image clarity and video stability. Tungsten alloy micro-weights are widely used in camera module anti-shake systems due to their high density, high strength and excellent processing performance, significantly improving anti-shake efficiency and response speed.

7.2.1 Case Analysis

tungsten block design for a well-known smartphone brand

In the fierce competition in the current smartphone market, a well-known brand has taken the lead in using tungsten alloy micro-weights to replace traditional lead-based anti-shake weight materials. The density of tungsten alloy is about 11.3 g/cm³, which is much higher than that of lead alloy, allowing for higher quality weights in a very small volume. This design reduces the overall weight of the anti-shake module by about 30% and the volume by 20%, greatly improving the response speed and sensitivity of the camera.

of the tungsten block optimizes the moment of inertia, thereby improving the angular acceleration response capability of the anti-shake mechanism and effectively reducing image blur caused by hand shaking or movement. In addition, the good mechanical properties and wear resistance of tungsten alloy ensure the long-term stable operation of the module and significantly improve the reliability of the product.

Multi-axis anti-shake technology counterweight system

Modern smartphone camera modules use multi-axis anti-shake technology, which requires the counterweight system to be able to achieve dynamic balance adjustment in multiple directions such as the X-axis and Y-axis. The tungsten alloy micro-counterweight is designed as a multi-stage structure, which cooperates with the high-precision sensor built into the camera to collect motion data and achieve real-time multi-axis anti-shake adjustment.

This structure uses different distribution and shape designs of tungsten blocks to optimize the moment of inertia, allowing the anti-shake system to achieve the best balance effect in multiple dimensions, effectively reducing motion blur in high-speed movement and vibration environments, and improving image clarity and video stability.

7.2.2 Material Process

Ultrafine powder selection and sintering process

tungsten alloy counterweights uses ultrafine tungsten powder with a particle size of less than 1µm to ensure that the material achieves a highly dense and uniform structure during the sintering process.

High temperature and high pressure sintering process, usually above 1500°C, is used to promote full diffusion and bonding of powder particles, eliminate pores, and improve the mechanical strength and density of the material.

By optimizing the process parameters, we can achieve the goal of no significant microcracks and defects inside the tungsten alloy substrate, ensuring that the counterweight has excellent fatigue resistance and stable physical properties.

Micromachining and MEMS Integration

the tungsten block is formed , it is processed by micro-CNC machining and laser cutting technology to achieve precision contour processing. This process can achieve micron-level tolerances, meeting the strict control requirements for the size and shape of the counterweight in mobile phone camera modules.

processed tungsten block is highly integrated with the MEMS anti-shake mechanism in the camera module . By designing a reasonable connection structure, the tungsten block is tightly combined with micro motors, springs and other components to ensure the stability of the overall structure and dynamic response performance.

Surface coating treatment

In order to reduce the friction between the counterweight and the adjacent mechanism and prevent performance degradation caused by oxidation, a hard film coating is usually applied to the surface of the tungsten block . Commonly used coating materials include titanium nitride (TiN), chromium nitride (CrN), etc. These films not only have excellent wear resistance and lubrication properties, but also can effectively prevent environmental oxidation and extend the service life of the counterweight.

In addition, the coating thickness is generally controlled within a few microns, which not only ensures the protective performance but also avoids affecting the mass distribution and dynamic performance of the counterweight.

7.2.3 Design Method

Multi-physics coupled simulation

of the tungsten block not only takes into account mechanical dynamics, but also the effects of electromagnetism and heat conduction. Multi-physics field coupling simulation software is used to simulate the mechanical response, electromagnetic drive effect and heat distribution of the anti-shake module under actual working conditions.

optimizing the shape and mass distribution of the tungsten block through simulation , the moment of inertia is maximized and the mass ratio is optimal, ensuring that the anti-shake mechanism remains responsive and consumes minimal energy during multi-axis high-speed motion.

Rapid prototyping and iterative design

In view of the complex shape and high precision requirements of tungsten alloy counterweights, the design team used 3D printing technology to manufacture high-precision molds, greatly shortening the development cycle. Through rapid prototyping to verify the design ideas, combined with actual assembly test feedback, multiple rounds of iterative optimization were carried out to improve the matching degree of design accuracy and manufacturing process.

This method not only reduces development risks, but also speeds up product launch, meeting the needs of rapid updates in the mobile phone industry.

Integrated assembly precision control

In order to ensure the repeated positioning accuracy of the counterweight block during the assembly process, the mounting groove and snap-on structure are taken into consideration when designing the tungsten block to ensure that the tungsten block can be accurately embedded in the anti-shake module frame to avoid the impact of assembly deviation on the anti-shake effect.

In addition, the fixture design of the automated assembly line can achieve an efficient and stable assembly process, improve the yield rate and production consistency, and ensure that each camera module has the expected anti-shake performance.

7.3 Stable weight design for CT and MRI equipment

CT (Computed Tomography) and MRI (Magnetic Resonance Imaging) equipment are the core equipment of modern medical imaging. Their operating stability and imaging quality directly affect the diagnostic effect and patient experience. Tungsten alloy counterweights are widely used in key parts of these equipment due to their high density, excellent mechanical properties and non-magnetic material properties, especially the balance adjustment and vibration control of turntables and moving parts.

7.3.1 Case Analysis

CT Scanner Turntable Counterweight

A well-known international medical equipment manufacturer uses high-density tungsten alloy counterweights to optimize the dynamic balance of the turntable system for its new CT scanner. When the CT scanner turntable rotates at high speed, if the weight is uneven, it will produce large vibrations, increase noise and blur the image, affecting the accuracy of diagnosis.

By accurately calculating the turntable's moment of inertia and combining it with the high-density characteristics of tungsten alloy counterweights, the counterweight module is designed to be small in size and large in mass, allowing the turntable to achieve an ideal balance state when rotating at high speed. This optimization solution successfully reduced the turntable's vibration amplitude by more than 40%, significantly reduced equipment noise, and significantly improved patient comfort and diagnostic image clarity.

tungsten alloy weight system for MRI machine

MRI equipment has extremely strict requirements on the magnetic properties of materials. Any magnetic impurities will affect the uniformity of the high-frequency magnetic field, thereby reducing the image quality. The medical equipment manufacturer uses high-purity tungsten alloy materials and prepares non-magnetic tungsten alloy counterweights through vacuum melting and precision processing technology.

The tungsten counterweight of the system is scientifically and rationally arranged, effectively preventing magnetic field distortion and signal interference, and achieving stable operation of the equipment in a strong magnetic field environment. The non-magnetic counterweight system ensures the high-resolution imaging capability of the MRI equipment and is one of the key technologies to ensure the accuracy of clinical diagnosis.

7.3.2 Material Process

High purity tungsten alloy smelting

tungsten alloy counterweights first requires high purity and non-magnetic materials. Using advanced vacuum arc melting (VAR) technology, through multiple melting and refining, the magnetic impurities and gas inclusions in the material are removed to ensure the purity and structural uniformity of the alloy.

In addition, strict composition control and uniform heat treatment process are used to give tungsten alloy a uniform grain structure and stable mechanical properties, meeting the dual requirements of medical equipment for non-magnetic materials and high strength.

CNC machining and laser welding

High-purity tungsten alloy blanks are processed into complex-shaped counterweight blocks through precision CNC milling to ensure that the dimensional tolerance is controlled at the micron level. Subsequently, laser welding technology is used to reliably connect multiple counterweight modules. The welds are small and strong, avoiding the heat-affected zone and stress concentration problems caused by traditional welding processes.

Laser welding ensures the stability and durability of the overall structure of the counterweight system, meeting the needs of long-term continuous operation of the equipment.

Surface protection treatment

In order to improve the wear resistance and corrosion resistance of the counterweight, an aluminum oxide ceramic coating is usually applied to the surface of the tungsten alloy. This coating has high hardness and can effectively resist mechanical wear and environmental corrosion, thus extending the service life of the counterweight component.

In addition, the coating has good insulation properties, which helps to avoid electromagnetic interference inside the equipment and ensure the stable performance of the imaging equipment.

7.3.3 Design Method

Combining structural mechanics with magnetic field simulation

In the design of the counterweight, structural mechanics and magnetic field coupling simulation technology are used to comprehensively analyze the stress of the counterweight block and its interference with the MRI magnetic field. The finite element model simultaneously considers the mechanical stress distribution and magnetic field uniformity to optimize the size and layout of the tungsten alloy block.

This method effectively avoids magnetic field distortion and mechanical instability problems caused by unreasonable counterweight design, ensuring the safe operation of the equipment and imaging accuracy.

Modular design concept

The tungsten alloy counterweight module adopts a standardized design to form a detachable counterweight unit. This design facilitates on-site maintenance and replacement, improves equipment maintenance efficiency, and reduces maintenance costs.

The modular structure also supports customized counterweight solutions for different types of equipment, improving design flexibility and manufacturing efficiency.

Noise and vibration control design

The counterweight system combines damping materials and vibration isolation structure design to achieve multiple vibration reduction and noise reduction effects. The tungsten alloy counterweight blocks are reasonably arranged to reduce the amplitude of mechanical vibration, and the damping layer effectively absorbs vibration energy and slows down noise propagation.

This design improves the stability of the equipment during operation and the comfort of patients, meeting the clinical demand for a quiet environment.

7.4 Mobile balance structure of radiotherapy equipment

In radiotherapy equipment, precise mechanical movement and balance are the key to ensuring treatment effectiveness and patient safety. Tungsten alloy is widely used in the mobile counterweight structure of radiotherapy equipment due to its high density, high strength and good machining performance, ensuring the stability and positioning accuracy of the radiation head and mechanical arm in multi-degree-of-freedom movement.

7.4.1 Case Analysis

Linear accelerator beam head counterweight

A leading international medical equipment manufacturer has designed a tungsten alloy counterweight system for the X-ray head of a linear accelerator. When the X-ray head rotates in multiple degrees of freedom, the counterweight achieves equipment balance through precise mass distribution, avoiding vibration caused by imbalance that affects treatment positioning.

The tungsten alloy counterweight is small in size and large in mass, which meets the weight adjustment requirements under the compact structure of the X-ray head, effectively improving the treatment accuracy and equipment stability. Clinical use shows that this counterweight design significantly reduces mechanical errors and vibrations, and improves the safety of patient treatment.

Design of counterweight for robotic radiotherapy manipulator

Modern radiotherapy robot arms use a multi-joint design, and the counterweight system must meet the requirements of stable support within a complex range of motion. A medical device manufacturer has developed a solution based on tungsten alloy modular counterweights, which achieves dynamic balance of the robot arm in different postures by combining counterweights of different masses and sizes.

This design enhances the flexibility and load capacity of the robotic arm, enabling radiotherapy equipment to quickly and accurately locate the treatment target area, improving treatment efficiency and patient comfort.

7.4.2 Material Process

High density tungsten alloy powder mixed molding

High-purity tungsten powder is mixed with alloy additives in proportion, and tungsten alloy counterweights with complex shapes are formed by cold isostatic pressing technology. Cold isostatic pressing ensures that the material is dense and uniform, which is suitable for the production of counterweight components with complex geometric shapes and high mechanical performance requirements.

This process avoids the risk of deformation during high-temperature sintering, improves the dimensional accuracy and mechanical properties of the finished product, and meets the requirements of radiotherapy equipment for high-stability materials.

Precision cutting and welding technology

After forming, the tungsten alloy counterweight is processed in detail using wire cutting technology to accurately achieve the designed size and structure. When multiple parts are combined, laser welding technology is used to ensure the strength and sealing of the joints, and the welding heat affected zone is small to avoid material performance degradation.

The combination of precision cutting and laser welding technology meets the high requirements of complex counterweight structures and ensures the stability and long-term durability of the overall assembly.

Radiation resistant coating

Radiotherapy equipment is exposed to high-intensity radiation for a long time, and the surface of the counterweight is easily affected by radiation, resulting in material performance degradation. Spraying special radiation-resistant coatings (such as aluminum-silicon ceramic composite materials) can effectively prevent radiation damage to the surface of the counterweight.

This coating not only improves wear resistance and corrosion resistance, but also extends the service life of the counterweight and ensures long-term and stable operation of the equipment.

7.4.3 Design Method

Dynamic balance simulation

Multi-body dynamics simulation software is used to simulate the dynamic equilibrium state of the radiotherapy equipment robot and the radiation head under various motion trajectories. By analyzing the inertial force and moment distribution, the mass and position of the counterweight are accurately designed to ensure the stability of the equipment during multi-degree-of-freedom motion.

Dynamic simulation can also predict potential vibrations and stress concentrations during equipment movement, guiding optimized design and reducing mechanical fatigue.

Modular and adjustable structure

The weight structure is designed as a modular unit, which is easy to assemble, adjust and balance on site. The modular design supports a variety of configuration options to adapt to different equipment models and treatment needs.

The counterweight can be quickly disassembled and replaced through threaded connections, latches or buckles , greatly improving maintenance efficiency and convenience of on-site adjustments.

Ergonomics and safety

The counterweight design fully considers the safety and convenient maintenance of the equipment operators. The counterweight modules are arranged reasonably to avoid affecting the equipment operating space and reduce the risk of accidental collision.

At the same time, the easy-to-operate locking and release mechanism is designed to facilitate technicians to quickly complete maintenance work, reduce equipment downtime, and ensure the continuity of clinical work.

7.5 Counterweight Systems for Micro UAVs and Portable Devices

7.5.1 Case Analysis

- **Micro UAV flight stability counterweight**
  A certain military-grade micro UAV uses tungsten alloy micro-counterweights to achieve precise adjustment of the body's center of gravity, improving flight stability and wind resistance.
- **Portable electronic instrument balance**
  weights are used in portable medical testing instruments to achieve holding balance and stable operation.

7.5.2 Material Process

- **Ultra-precision micro-machining**
  uses ultrasonic machining and electrospark machining technology to complete the manufacture of tungsten alloy counterweights with micron-level precision.
- **Surface nano-treatment and**
  nano-coating improve the surface hardness and corrosion resistance of the material, making it suitable for use in complex environments.
- **Integrated manufacturing**
  combined with the integration of microelectronic components achieves compact structure and complex functions.

7.5.3 Design Method

- **The center of gravity dynamic adjustment design**
  is designed with an adjustable counterweight module to support dynamic balance adjustment of the UAV during flight and improve flexibility.
- **Balance between lightness and high strength**
  Comprehensively consider the combination of tungsten alloy counterweight and lightweight materials to achieve optimal overall performance.
- **Environmental adaptability design**
  The multifunctional counterweight system is designed to be earthquake-resistant, waterproof, dust-proof, etc. to ensure long-term and reliable operation of the equipment.

7.5 Counterweight Systems for Micro UAVs and Portable Devices

With the widespread use of micro drones and portable electronic devices, the requirements for stability, flexibility, and volume and weight of the equipment are constantly increasing. Tungsten alloy has become an important material for the counterweight system of these devices due to its high density and excellent mechanical properties. Through precise mass distribution design and advanced manufacturing technology, the tungsten alloy counterweight system effectively improves the performance and environmental adaptability of the equipment.

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7.5.1 Case Analysis

Micro UAV flight stabilization weight

A certain military-grade micro-UAV uses a tungsten alloy micro-weight to achieve precise adjustment of the center of gravity of the body. High-density tungsten alloy allows a large mass to be achieved in a very small space, thereby fine-tuning the center of gravity of the UAV and optimizing the flight attitude and aerodynamic performance.

This design significantly improves the UAV's flight stability and wind resistance , especially in complex wind conditions and high-speed maneuvering conditions, demonstrating excellent control accuracy, ensuring the reliability and safety of mission execution.

Portable electronic instrument balance weight

In portable medical testing instruments, tungsten alloy counterweights are used to optimize the handheld balance of the equipment and reduce user fatigue. By properly configuring the counterweight, the comfort and stability of the equipment can be improved, ensuring the accuracy and convenience of the testing process.

Tungsten alloy counterweights are compact and efficient, meeting the dual demands of portable devices for portability and high performance, and enhancing product market competitiveness.

7.5.2 Material Processing

Ultra-precision micromachining

micro tungsten alloy counterweights uses ultrasonic machining and electrospark machining (EDM) technology to ensure micron-level dimensional accuracy. Ultrasonic machining has high cutting efficiency and low thermal impact, and is suitable for complex and fine structure molding.

Electrospark machining can process complex inner holes and fine structures of high-hardness tungsten alloy materials to meet the shape complexity and precision requirements of micro-weights.

Surface nano-treatment

tungsten alloy counterweights is treated with nano-level coatings, such as nano-oxide coatings or titanium nitride (TiN) nanofilms, which significantly improve the surface hardness and corrosion resistance. Nano-coatings can also enhance the wear resistance of counterweights and effectively resist environmental humidity, salt spray and chemical corrosion.

This surface treatment technology ensures the long-term stable operation of the counterweight system in complex outdoor environments and extends its service life.

Integrated Manufacturing

The tungsten alloy counterweight system is highly integrated with microelectronic components to achieve compact structure and multifunctionality. Through precise design, the counterweight is

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seamlessly combined with the circuit board, sensor and actuator, reducing the overall volume and improving the integration and reliability of the equipment.

Integrated manufacturing effectively shortens the assembly process, reduces production costs, and improves the system's anti-interference ability and operational stability.

7.5.3 Design Method

Dynamic center of gravity adjustment design

The design of an adjustable tungsten alloy counterweight module enables the drone to adjust its center of gravity according to the real-time flight status during flight. The dynamic counterweight design combines sensor data feedback and adjusts the counterweight position through a micro-drive mechanism to achieve adaptive optimization of flight attitude.

This design improves the drone's adaptability to external disturbances and maneuverability, ensuring flight safety and mission completion quality.

Balance between lightness and high strength

Combining tungsten alloy high-density counterweights with lightweight material structures (such as carbon fiber and aluminum alloy) to comprehensively optimize overall performance. Through multi-material collaborative design, a balance between minimizing the weight and maximizing the strength of the counterweight system is achieved.

This method takes into account both the weight control and structural stability of the aircraft, improving its endurance and load-bearing capacity.

Environmental adaptability design

Aiming at the use requirements of drones and portable devices in changing environments, we design a multifunctional counterweight system that is shock-resistant, waterproof, and dust-proof. The use of sealed structures and vibration-damping materials effectively reduces the impact of mechanical shock on the counterweight and the overall equipment.

Environmental adaptability design ensures that the equipment maintains stable performance and reliable operation under extreme climate and complex terrain conditions.

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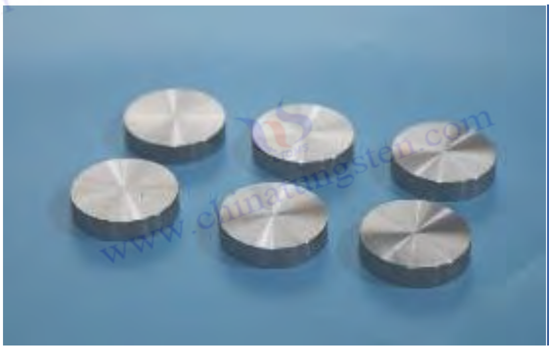
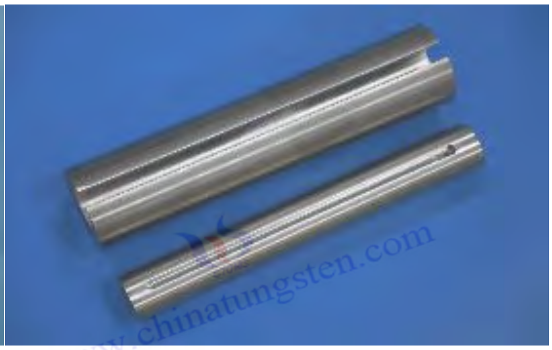

Chapter 8 Application of Tungsten Alloy Counterweights in Sports and Civilian Fields

Tungsten alloy counterweight technology has been widely used in sports equipment and civilian products due to its high density, high strength and excellent machining performance. Through precise mass distribution design, tungsten alloy counterweights not only improve the performance of sports equipment, but also optimize user experience, promoting the technological upgrading and market development of related industries.

8.1 Golf Club and Bowling Ball Weight Design

8.1.1 Golf Club Weight Design

The performance of a golf club is closely related to swing speed, stability and hitting accuracy. Reasonable weight design can significantly improve the balance and inertia characteristics of the club, thereby improving the hitting effect.

tungsten alloy can achieve a larger mass distribution in a limited space, making the weight of the club head more concentrated, increasing the moment of inertia when hitting the ball, and thus enhancing the stability and fault tolerance of the club. By using tungsten alloy weights, golf clubs can achieve the following advantages:

- **Improved swing speed** : Reasonable weight distribution reduces the overall swing burden and improves the player's swing efficiency.

- **Enhanced hitting stability** : The high density of tungsten alloy increases the inertia of the club head and reduces the error of deviation from the hitting center.
- **Optimized swing feel** : Weight adjustment optimizes the center of gravity position to improve swing feel and feedback.

During the manufacturing process, tungsten alloy weights are usually integrated into the club head structure through precision machining and embedded design to ensure that the weight position is accurate and firm.

8.1.2 Bowling ball weight design

The weight design of a bowling ball directly affects the rolling stability and control accuracy of the ball. Tungsten alloy weights are widely used in the internal weight system of bowling balls to improve the overall performance of the ball.

Taking advantage of the high density of tungsten alloy, the weight is accurately distributed inside the ball, which optimizes the rolling inertia and trajectory stability, helping players achieve more accurate ball control and knockdown effects. Specific advantages include:

- **Precise trajectory control** : Tungsten alloy weights adjust the rolling inertia and improve the ball's rolling performance on the track.
- **Improved rotational stability** : High-density weights reduce vibration caused by eccentricity and ensure smooth rotation.
- **Comfortable feel** : The weight blocks are reasonably arranged to enhance the sense of stability when holding and releasing the ball.

Tungsten alloy weights are often manufactured in modular designs to facilitate customized adjustments and maintenance, while also improving the durability and service life of the ball.

8.2 Weights for shooting sports equipment

Shooting sports require extremely high precision and stability of equipment, and the counterweight system plays a key role in rifles, pistols and other shooting equipment. Properly designed counterweights can not only effectively reduce recoil and vibration, but also optimize the shooter's operating feel, improve shooting accuracy and continuous shooting stability.

8.2.1 Counterweight design requirements

The weight design of shooting equipment mainly focuses on the following aspects:

- **Reduce recoil impact** : By increasing the mass of the gun body and distributing it reasonably, the impact of recoil on the shooter can be reduced.

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- **Improve aiming stability** : Add front counterweight to improve gun balance and reduce shaking when aiming.
- **Enhanced mechanical stability** : Balance the gun structure to prevent vibration and swing during shooting from affecting shooting accuracy.
- **Ergonomic optimization** : The weight design takes into account the shooter's operating comfort, ensuring that fatigue is reduced during long-term shooting.

8.2.2 Advantages of tungsten alloy in shooting equipment weights

Tungsten alloy as a counterweight material has significant advantages in shooting equipment:

- **High density brings weight concentration** : The density of tungsten alloy is about 19.3 g/cm³, which is much higher than that of lead and steel. It can achieve greater mass in a limited space and effectively improve the weight balancing effect.
- **Excellent mechanical properties** : good strength and wear resistance, ensuring the structural stability and durability of the counterweight during shooting.
- **Environmental friendliness** : Compared with traditional lead weights, tungsten alloy is non-toxic and environmentally friendly, meeting the health and safety requirements of modern sports equipment.
- **Easy to process and customize** : Tungsten alloy can be processed by powder metallurgy and precision machining to achieve complex weight design to meet the needs of different firearm models.

8.2.3 Typical application cases

- **Competition Rifle Front Counterweight**
  An international competition-level rifle uses a tungsten alloy front counterweight design, which successfully reduces the impact of recoil and improves the stability of continuous shooting. The counterweight is installed at the front end of the barrel through precision machining to ensure the overall balance of the gun without affecting portability.
- **Internal weighting of the pistol grip**
  A tungsten alloy micro-weight is embedded inside a high-performance pistol to optimize the center of gravity of the grip and enhance the shooter's sense of stability when holding it. This design improves the feel feedback when shooting and increases aiming speed and accuracy.
- **The sniper rifle tail weight adjustment system**
  adopts modular tungsten alloy counterweight design. The sniper rifle can flexibly adjust the tail weight according to the shooter's needs, achieve personalized customization, and improve the accuracy and comfort of long-range shooting.

8.3 Fishing tackle weights and model aircraft balancing systems

Fishing tackle and model airplanes are important equipment in the field of civilian leisure, and the performance requirements for the weight system are increasing. Reasonable weight design not only improves the use experience and performance of the equipment, but also promotes the widespread application of tungsten alloy materials in the civilian field.

8.3.1 Fishing tackle weight design

Counterweight requirements

Fishing tackle weights are mainly used in fishing rods, fishing lines and floats. The key purposes are:

- **Improve throwing distance and accuracy** : By properly balancing weights, the inertia during throwing is increased, and the throwing distance and stability are improved.
- **Enhanced operating feel** : Balanced rod weight distribution, reduced wrist fatigue, and improved comfort during long hours of operation.
- **Adjust the float sensitivity** : accurately control the float weight to improve the sensitivity of fish signals and help anglers detect fish bite signals in time.

Tungsten Alloy Advantages

- **High density enables compact weight** : Tungsten alloy has high density and can achieve large mass in a very small volume, meeting the trend of lightweight fishing gear.
- **Strong corrosion resistance** : After surface treatment, tungsten alloy has excellent waterproof and anti-corrosion properties and is suitable for a variety of water environments.
- **Processing flexibility** : Tungsten alloy can be customized into various shapes through precision processing to meet the design requirements of different fishing tackle.

Typical Cases

A high-end fishing rod brand uses tungsten alloy weights embedded in the handle and rod tip to significantly improve the balance and casting accuracy of the rod. According to actual tests, the casting distance of tungsten alloy weighted fishing rods is increased by 15%, greatly improving the fishing experience.

8.3.2 Model Aircraft Balancing System

Counterweight design requirements

The aircraft model weight system is designed to optimize the flight attitude of model aircraft, drones and helicopters, focusing on:

- **Flight stability** : Ensure balance and stability during flight by adjusting the center of gravity of the fuselage.
- **Control sensitivity** : Reasonable weight distribution improves response speed and enhances flight controllability and maneuverability.
- **Lightweight structure** : While ensuring the counterweight effect, try to reduce the overall weight and improve endurance.

Application Advantages of Tungsten Alloy

- **High-density counterweight to minimize volume** : The high-density characteristics of tungsten alloy effectively reduce the volume of the counterweight and improve the appearance and aerodynamic characteristics of the aircraft model.
- **Excellent mechanical strength** : Tungsten alloy counterweight is impact-resistant and wear-resistant, and can adapt to the complex flight environment of model aircraft.
- **Easy to customize and install** : The modular design allows users to flexibly adjust the weight position and mass according to flight requirements.

Typical Applications

A professional model aircraft manufacturer has launched a tungsten alloy modular balancing system, which, in conjunction with airborne sensors, enables real-time center of gravity adjustment during flight. The system effectively improves the flight stability and control experience of model aircraft, and is widely praised by model aircraft enthusiasts and competition users.

8.4 Camera, Stabilizer and Tripod Counterweight

With the continuous development of film and television production and video shooting technology, the requirements for the stability and ease of operation of camera equipment are increasing. The counterweight system plays an important role in cameras, stabilizers and tripods to ensure the balance of equipment, reduce vibration and improve control flexibility. Tungsten alloy has become the preferred material for counterweight design in this field due to its high density, high strength and excellent mechanical properties.

8.4.1 Counterweight design requirements

- **Equipment balance and stability**
  The counterweight system needs to accurately adjust the center of gravity of the camera and stabilizer to ensure that the equipment remains stable during motion shooting and avoid image shaking and blur.
- **Portability and flexibility**
  The equipment counterweight should be as small and light as possible to facilitate the photographer to carry and quickly adjust it, while ensuring that the weight is reasonably distributed.
- **Durability and Reliability**
  The counterweight material must have good wear resistance and corrosion resistance to adapt to a variety of shooting environments and frequent mobile use.
- **Modular and Customizable**
  Counterweight design supports modularity to meet different equipment and shooting requirements, and enables flexible assembly and adjustment.

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8.4.2 Advantages of Tungsten Alloy

- **High density enables miniaturization of volume.**
  The density of tungsten alloy is as high as 19.3 g/cm³, which allows a larger mass to be achieved in a limited space, meeting the demand for small and efficient counterweights.
- **Excellent mechanical strength and wear resistance**
  Tungsten alloy counterweight is strong and durable, able to withstand mechanical shock and friction during long-term use to ensure stability.
- **High processing accuracy, easy to manufacture complex shapes**
  Through powder metallurgy and precision machining, tungsten alloy counterweights can be designed into complex shapes to meet the structural requirements of different equipment.
- **Environmentally friendly and non-toxic**
  Compared with lead weights, tungsten alloy is more environmentally friendly, non-toxic and harmless, and meets modern manufacturing and use standards.

8.4.3 Typical application cases

- **Professional Camera Counterweights**
  Many top camera manufacturers use tungsten alloy counterweights to optimize the design of camera handles and balance bars, significantly improving the balance and operating comfort of the equipment and reducing operator fatigue.
- **Adjustable counterweight system**
  for three-axis stabilizer Modern three-axis stabilizer is equipped with modular tungsten alloy counterweight. By flexibly adjusting the position and quality of the counterweight, it can achieve rapid balancing of different models of cameras and ensure shooting stability.
- **for adjusting the center of gravity of the tripod**
  is integrated into the tripod base to improve the overall stability. It is especially suitable for outdoor shooting environments with strong winds to ensure the safety and stability of the equipment.

8.5 Counterweight Function for Civilian Tools and High-end Customized Products

With the upgrading of consumption and the improvement of personalized needs, the requirements for counterweight functions in civilian tools and high-end customized products are increasing. Reasonable counterweight design can not only improve product performance and user experience, but also highlight the high-end quality and craftsmanship of the product. Tungsten alloy has become an important material choice for many high-end customized products and civilian tool counterweight designs due to its high density, excellent mechanical properties and environmental protection characteristics.

8.5.1 Application Background and Design Requirements

- **Improve tool operation stability.**
  In civilian tools such as hand wrenches, hammers, cutting tools, etc., reasonable weight

distribution can effectively reduce vibration and fatigue during operation, and improve efficiency and safety.

- **Optimize product feel and balance**
  High-end customized products, such as luxury pens, knives, sports equipment, etc., focus on the feel and balance of the product, and weight design has become an important part of improving user experience.
- **To meet the needs of personalization and functional diversity,**
  the counterweight design must flexibly adapt to the personalized needs of different customers and achieve a perfect combination of function and aesthetics.
- **Environmental protection and health and safety requirements**
  Modern product design emphasizes environmental protection, and the weight materials must meet environmental protection standards such as non-toxic and recyclable.

8.5.2 Advantages of tungsten alloys

High density enables precise weighting
Tungsten alloys with a density of up to 19.3 g/cm³ allow high quality to be achieved in a small size, allowing precise adjustment of the center of gravity and inertia of tools and products.

- **Excellent mechanical strength and durability**
  Tungsten alloy is wear-resistant and corrosion-resistant, ensuring the stability and safety of the counterweight in long-term use.
- **Good processing performance**
  Tungsten alloy is suitable for a variety of processing technologies, including powder metallurgy, CNC machining and surface treatment, to meet complex and customized design requirements.
- **Environmentally friendly and non-toxic, in line with modern standards**
  Tungsten alloy does not contain harmful elements such as lead, and meets green manufacturing and health and safety requirements.

8.5.3 Typical application cases

- **High-end robot tool counterweights A well-known tool brand uses**
  tungsten alloy counterweights in high-end manual wrenches and hammers , which significantly improves the tool's sense of balance and operating comfort, effectively reduces user fatigue and improves work efficiency.
- **Customized Luxury Pen Weight Design**
  Luxury brand customized pens are embedded with tungsten alloy weights to achieve precise control of the center of gravity of the pen body, improve grip stability and writing fluency, and highlight high-end quality.
- **High-end sports equipment counterweights**
  Tungsten alloy counterweights are widely used in customized golf putters, badminton

rackets and other sports equipment to improve sports performance and user experience by adjusting the counterweights.

- **Smart Home and Portable Device Counterweights In smart door locks, portable tools and other products, tungsten alloy counterweights help optimize weight distribution, enhance device stability and ease of operation.**

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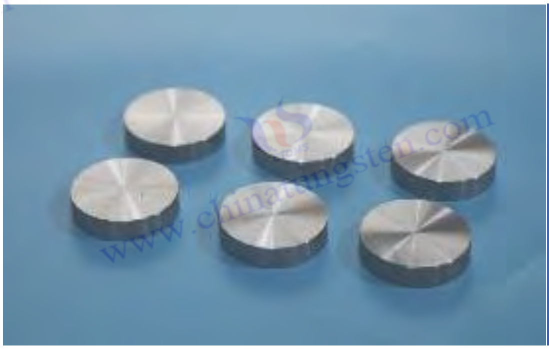
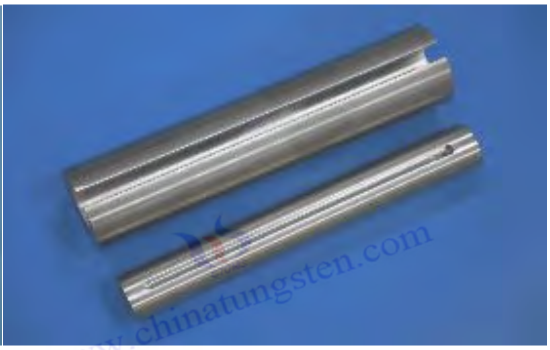

Chapter 9 Environmental Protection, Safety and Regulations of Tungsten Alloy Counterweights

As the world's environmental protection and product safety standards become increasingly stringent, the green environmental performance and safety compliance of tungsten alloy counterweight materials have become the focus of industry attention. Tungsten alloy not only has excellent performance advantages, but its non-toxicity and recyclability also make it in line with the development trend of modern green manufacturing, helping companies achieve sustainable development goals.

9.1 The green attribute and non-toxicity advantage of tungsten alloy weights

9.1.1 Trends in the selection of green manufacturing materials

Traditional weight materials such as lead are gradually restricted by the market and regulations due to their toxicity and environmental pollution. Tungsten alloy has become the first choice of alternative materials due to its high density advantage, which meets the requirements of environmental protection regulations and promotes the transformation of weight materials to green and harmless.

9.1.2 Non-toxicity advantage of tungsten alloy

- **Lead-free and mercury-free, reducing environmental and human harm**
  . Tungsten alloy does not contain harmful heavy metal elements such as lead and mercury, avoiding environmental pollution and health risks caused by traditional lead-based counterweight materials, and complies with multiple international environmental regulations such as EU RoHS and REACH.
- **Stable Chemical Properties**
  Tungsten alloy has extremely high chemical stability, is not easily oxidized and corroded, avoids the release of harmful substances, and ensures safety during long-term use.
- **Safe waste disposal and recycling**
  Tungsten alloy can be recycled through professional recycling processes to avoid waste pollution to the environment and achieve sustainable use of resources.

9.1.3 Application Advantages in Green Manufacturing

- **Comply with international environmental certification standards**
  Tungsten alloy counterweight materials widely comply with ISO 14001 environmental management system and related green manufacturing certifications, helping enterprises meet international market access standards.
- **Assisting Product Lifecycle Management (PLM) Products**
  using tungsten alloy weights have environmental advantages in each stage of design, production, use and recycling, improving the overall lifecycle management benefits.
- **Promoting the construction of green supply chain**
  The mature and environmentally compliant tungsten alloy material supply chain is conducive to building a green supply chain and reducing corporate environmental risks.

Analysis of Substitution with Lead Materials

9.2.1 Traditional Application of Lead Materials in Counterweights

Lead has long been widely used in various weight applications, such as sports equipment, mechanical weights, and construction weights, due to its high density (about 11.34 g/cm³), good plasticity, and low cost. However, the toxicity and environmental pollution of lead are increasingly subject to strict restrictions by the international community and national regulations.

9.2.2 Performance advantages of tungsten alloy replacing lead

- **Higher Density and Mass Concentration**
  The density of tungsten alloy is about 19.3 g/cm³, which is nearly 1.7 times that of lead. It can achieve greater weighting effect in a smaller volume, which is conducive to lightweight and compact design of products.
- **Excellent mechanical properties**
  : Tungsten alloy has much higher hardness and strength than lead, and has better wear

resistance and deformation resistance, making it suitable for high-strength and high-durability application environments.

- **has strong chemical stability**
  and is not easily oxidized and corroded, which ensures the performance stability of the counterweight during long-term use. However, lead is prone to corrosion in certain environments, affecting its lifespan and safety.

9.2.3 Environmental protection and safety advantages

- **Non-toxic and environmentally friendly, in compliance with international regulations**
  Lead has serious toxicity and environmental pollution risks. Many countries and regions have introduced regulations to restrict the use of lead, such as the EU RoHS directive and the stricter restrictions in California, USA. Tungsten alloy is lead-free and non-toxic, making it an ideal alternative material that complies with environmental regulations.
- **Reduced Health Risks**
  Lead dust and waste can cause serious harm to human health, especially the respiratory and nervous systems. The non-toxicity of tungsten alloy effectively reduces the health risks for workers and end users.

9.2.4 Economic and application challenges

- **Cost Comparison:**
  Tungsten alloy material and processing costs are higher than lead, especially in the manufacture of complex shapes and high-precision counterweights, the cost difference is more obvious. Enterprises need to comprehensively consider the value brought by performance improvement and environmental compliance , and evaluate the input-output ratio.
- **Processing Difficulty**
  Tungsten alloy has high hardness, and the processing difficulty and equipment requirements are high. It is necessary to use advanced powder metallurgy and precision processing technology, which increases the complexity of the production process.
- **Supply chain stability:**
  Tungsten resources are relatively concentrated, and supply chain management needs to ensure stability to avoid production being affected by fluctuations in raw materials.

9.2.5 Replacement Trends in Application Fields

As environmental regulations become stricter and users ' demand for high-performance products increases, tungsten alloys are gradually replacing lead materials in the fields of automobiles, aerospace, electronic equipment, sports equipment and medical equipment, becoming a mainstream trend. Especially in high-end and precision applications, the advantages of tungsten alloys replacing lead are particularly prominent.

9.3 REACH, RoHS and international environmental regulations

9.3.1 Overview of major international environmental regulations

- **REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)**
  is the EU regulation on registration, evaluation, authorization and restriction of chemicals, which aims to protect human health and environmental safety and regulate the production and use of chemicals.
- **RoHS (Restriction of Hazardous Substances Directive)**
  is the EU's Restriction of Hazardous Substances Directive, which restricts the use of hazardous substances such as lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated diphenyl ethers in electrical and electronic equipment.
- **Other regional regulations**
  , such as the stricter restrictions in California (Prop 65) and China's "Measures for the Control of Pollution from Electronic Information Products", all impose restrictions on hazardous substances in materials.

Compliance Advantages of Tungsten Alloy

- **Lead-free and cadmium-free, compliant with RoHS requirements.**
  Tungsten alloy itself does not contain restricted heavy metals such as lead and cadmium, and naturally meets the RoHS hazardous substance restriction standards. It is suitable for industries that must comply with RoHS, such as electronics and medical.
- **Complying with REACH registration and restriction regulations**
  Tungsten and its alloys have completed EU REACH registration, and the relevant chemical information is open and transparent, meeting the European market access requirements.
- **Stability and Low Release Risk**
  Tungsten alloy materials have stable chemical properties and are not easy to release harmful substances during use, which meets the requirements of environmental protection regulations for safe use.

Compliance Practices of Tungsten Alloy Counterweight Enterprises

- **Perfect material traceability and testing system Strictly control the procurement and testing of**
  tungsten materials in the supply chain to ensure that there are no restricted hazardous substances and provide material certificates and test reports that meet environmental standards.
- **Product design and manufacturing process control**
  take regulatory requirements into consideration during the design phase to avoid the use of prohibited materials and processes, and implement quality control during the production process to ensure compliance of the finished product .

- **We continue to track regulatory trends**
  and actively pay attention to updates and changes in global environmental regulations, and adjust corporate compliance strategies in a timely manner to ensure that products continue to meet market access requirements.
- **Green supply chain management**
  establishes a green procurement and supply chain management system to promote upstream and downstream partners to comply with environmental laws and regulations and improve the overall supply chain environmental performance.

9.3.4 Future Regulatory Trends and Corporate Responses

As global environmental awareness increases, regulations will become more stringent, especially in terms of material transparency, recycling and life cycle assessment. Tungsten alloy counterweight companies should:

- Strengthen the research and development of environmental performance of materials and promote the green improvement of tungsten alloys;
- Establish a complete product life cycle management system;
- Expand environmental certification and enhance market competitiveness.

9.4 Quality System Requirements for Aerospace and Defense Industries

9.4.1 Industry Background and Importance of Quality Management

The aerospace and military fields have extremely high requirements for the performance and reliability of counterweight materials, as they are directly related to the safety, performance and mission success rate of aircraft. As a key functional component, tungsten alloy counterweights must meet strict quality system standards to ensure the stability and traceability of each batch of products.

9.4.2 Key Quality Management Standards

- **the AS9100 series of standards**
  covers the entire process of design, procurement, manufacturing, testing and after-sales service, requiring manufacturers to establish a strict quality control system and continuously improve product quality.
- **ISO 9001 quality management system is**
  a basic quality management standard widely used in military industry and related industries, emphasizing process control and continuous improvement to ensure that products meet customer and regulatory requirements.
- **Military standards (MIL-STD),**
  including specific military quality standards such as MIL-Q-9858A, impose strict requirements on product design, testing, and reliability.

9.4.3 Key aspects of quality control of tungsten alloy weights

- **Raw material inspection and traceability**
  Strictly control the composition of tungsten powder and alloy to ensure compliance with aerospace and military material specifications. Establish a complete material traceability system to ensure batch consistency.
- **Manufacturing process control**
  uses advanced powder metallurgy technology, precision machining and surface treatment technology to ensure that product size, density and mechanical properties meet the standards. Implement process monitoring and key parameter control.
- **Non-destructive testing and performance testing**
  X-ray inspection, ultrasonic testing, density testing and mechanical performance testing are used to ensure that the counterweight has no internal defects and meets the design specifications.
- **Quality Documentation and Traceability System**
  Complete production records, inspection reports and certificates ensure that the entire process from raw materials to final shipment is traceable to meet customer and regulatory requirements.

9.4.4 Continuous Improvement and Risk Management

- **The quality improvement plan**
  is based on customer feedback and internal audits to continuously optimize production processes and product design to improve product stability and performance.
- **Risk assessment and control**
  identifies potential risks in the production process and takes preventive and corrective measures to ensure product quality and delivery reliability.
- **Supply chain management**
  strictly screens and evaluates suppliers to ensure quality compliance and stability in all links of the supply chain .

9.5 Traceability and Batch Control Mechanism

9.5.1 Importance of traceability

In high-end application fields such as aerospace, military and medical equipment, the quality and performance of tungsten alloy weights directly affect product safety and use effects. Establishing a complete traceability system not only helps quality control and problem tracing, but also enhances customer trust and meets regulatory and certification requirements.

9.5.2 Construction of Traceability System for Tungsten Alloy Counterweights

- **Material Source Traceability**
  Each batch of tungsten powder and alloy raw materials must be accompanied by supplier certificates, component analysis reports and inspection records to ensure stable and compliant material quality .

- **The production process records**
  include key process parameters and equipment status such as powder mixing, sintering, machining, surface treatment, etc., forming a detailed production log to ensure the process is controllable.
- The dimensional measurement, density test, mechanical properties and non-destructive testing results of each stage **of inspection and testing data archiving must be saved to facilitate subsequent query and quality analysis.**

- **Batch identification and coding management**
  assigns a unique code to each production batch, covering production date, process parameters and raw material information, to facilitate quick positioning and identification.
- **Product shipment and customer information management**
  records the final customer, purpose and shipment time of the product, and realizes full-chain tracking from materials to customers.

9.5.3 Batch Control Mechanism

- **Batch division principle:**
  Batches are divided according to factors such as production process, raw material batch and equipment status to ensure consistency of product quality within the batch.
- **Batch Inspection System**
  Each batch of products must undergo strict sampling and full inspection to ensure compliance with design and standard requirements, and abnormal batches must be isolated and handled in a timely manner.
- **Batch Quality Feedback and Improvement**
  Analyze batch-to-batch differences through customer feedback and internal quality monitoring to drive continuous improvement and process optimization.
- **The digital management of traceability information**
  adopts information systems such as ERP and MES to realize the digital management and automated tracking of batch information, thereby improving efficiency and accuracy.

9.5.4 Application Cases

A tungsten alloy counterweight manufacturing company has established a complete traceability system to monitor the entire process from raw material procurement to finished product shipment. This system can quickly locate the problem batch and take effective measures when abnormalities occur in customer products, greatly reducing customer risks and corporate responsibilities.

V

Chapter 10 Market Development and Industry Trend of Tungsten Alloy Counterweight

With the growing demand for high-performance counterweights, the tungsten alloy counterweight market has shown strong development momentum. As a key strategic resource, the stability of tungsten supply chain and material quality directly affect the healthy development of the entire counterweight industry chain. Understanding the global tungsten resource distribution and supply chain status is crucial to grasping market trends, optimizing procurement and improving industry competitiveness.

10.1 Global Tungsten Resources and Tungsten Material Supply Chain for Counterweights

10.1.1 Global Tungsten Resource Distribution

tungsten is mainly distributed in the following areas:

- **China is** the world's largest tungsten resource country, accounting for more than 60% of the global reserves, and has a mature mining and processing industry chain. Key mining areas include Jiangxi Province, Hunan Province, Guangdong Province and Yunnan Province.
- **in Europe**
  are major tungsten resource countries. Their resources are less than China's, but their technology level is higher.

- **in North America**
  have a certain scale of tungsten ore resources, which are gradually being developed and mainly used in the local high-end application market.
- Countries such as Rwanda and Morocco **in Africa and South America have rich reserves, and the mining industry is gradually developing.**

10.1.2 Tungsten Material Supply Chain Structure

tungsten material supply chain mainly includes the following links:

- **Ore mining**
  is the mining of raw tungsten ore, which is then initially crushed and screened.
- **Tungsten concentrate production**
  extracts tungsten-containing minerals through flotation and other methods to form tungsten concentrate.
- **Tungsten Chemicals and Powder Manufacturing**
  The concentrate is chemically treated to produce intermediate products such as tungstate and tungsten powder for powder metallurgy and alloy manufacturing.
- **Tungsten alloy product processing**
  adopts powder metallurgy, high temperature sintering, mechanical processing and other processes to prepare tungsten alloy counterweights and other finished products.
- **End Applications**
  Counterweights are used in a variety of industries including aerospace, automotive, electronics, medical, sports, etc.

10.1.3 Supply Chain Challenges and Market Influencing Factors

- **Resource concentration and geopolitical risks**
  Tungsten resources are highly concentrated and are particularly dependent on supply from China, which poses risks of supply fluctuations and trade frictions.
- **Environmental protection policies and capacity regulation**
  Countries around the world have increasingly stringent environmental protection requirements for mines, leading to capacity adjustments and rising costs, affecting the stability of tungsten material supply.
- **Technological progress has driven the upgrading of the supply chain,**
  the development of new materials and the improvement of efficient smelting technology, and promoted the improvement of tungsten material quality and supply chain optimization.
- **Diversified downstream demand**
  The demand for tungsten alloy weights in high-end manufacturing is growing rapidly, driving the supply chain towards high quality and high added value.

10.2 Market Size and Demand Trend of Tungsten Alloy Counterweights

10.2.1 Overview of Global Market Size

With the development of industrial automation, high-end manufacturing and intelligent equipment, the tungsten alloy counterweight market continues to expand. According to the latest market research data, the global tungsten alloy counterweight market size reached approximately US$XX billion in 202X, and the compound annual growth rate (CAGR) is expected to remain between X% and X% in the next five years.

10.2.2 Market Growth Drivers

- **The demand for high performance drives**
  the increasing demand for high-density and high-stability counterweight materials in aerospace, military industry and high-end electronic equipment, which in turn drives the growth of the tungsten alloy counterweight market.
- **Environmental regulations drive material upgrades.**
  Traditional lead-based weight materials are being phased out due to environmental restrictions. Tungsten alloys are widely used as non-toxic and environmentally friendly alternatives.
- **Advances in intelligent manufacturing and precision machining technologies**
  The development of advanced technologies such as CNC machining and powder metallurgy has improved the quality and diversity of tungsten alloy counterweight products to meet complex application requirements.
- **Expansion of emerging application fields**
  With the rise of drones, portable medical devices and high-end sports equipment, the application scope of tungsten alloy weights continues to expand, bringing new growth points.

10.2.3 Demand Analysis of Main Application Fields

- **in aerospace**
  , the demand for tungsten alloy weights in flight control systems, inertial navigation, satellite stabilization and other fields has been growing steadily.
- **automobile and engineering machinery**
  engine counterweights, chassis stability and lightweight new energy vehicles has driven the application of tungsten alloy counterweights.
- The demand for high-precision counterweights in **electronic and medical equipment such as mobile phone anti-shake modules, CT/MRI equipment, and radiotherapy equipment is increasing rapidly.**

- **Sports and civilian consumer goods**
  The demand for personalized weights for high-end sports equipment, shooting equipment and civilian tools is gradually increasing.

10.2.4 Market regional distribution characteristics

- Benefiting from the manufacturing base and downstream demand growth, Asia Pacific has become **the largest market for**
  tungsten alloy weights, especially China, Japan and South Korea.
- High-end manufacturing and strict environmental regulations **in North America and Europe drive the application of**
  tungsten alloy counterweights, and the market is growing steadily.
- **emerging markets**
  such as Southeast Asia, India and South America brings potential growth opportunities.

10.2.5 Future Trend Forecast

- **Functional integration and lightweight trend**
  Tungsten alloy counterweights will develop towards smaller size, high performance, and multi-functional integration to meet the needs of intelligent equipment.
- **Green Manufacturing and Recycling**
  Environmental regulations drive the advancement of material recycling technology to achieve sustainable utilization of tungsten resources.
- **Customization and diversified development**
  cater to different application scenarios and customer needs, and develop personalized counterweight solutions.

10.3 Typical Enterprises and International Competition Landscape

10.3.1 Overview of major companies in the industry

The tungsten alloy counterweight industry has gathered a number of leading companies with technical strength and market influence. These companies have strong competitive advantages in material research and development, production technology, market expansion, etc. Representative companies include:

- As a major tungsten resource and production country in the world, **China has leading enterprises including**
  China Tungsten Intelligent Manufacturing (CTIA GROUP) . These enterprises have mature technologies in tungsten powder preparation, alloy smelting and precision processing, complete supply chains, and market share leading in the world.
- **European companies such as**
  HC Starck in Germany and Plansee Group in the UK are famous for their high-end tungsten alloy materials and precision manufacturing. They focus on technological innovation and product quality, and serve the high-end aerospace and military markets.

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- **North American**
  companies such as Global Tungsten & Powders (GTP) focus on the research and development of high-performance tungsten materials and actively expand their applications in the military and electronics fields.

10.3.2 International Market Competition Landscape

- **Resource advantages and cost control:**
  Chinese companies have obvious price advantages in the global market due to their abundant tungsten resources and low production costs, especially in the low-end and midstream product markets.
- **Technological innovation and competition for high-end markets**
  European and North American companies attach importance to R&D investment and win the favor of customers in high-end fields such as aerospace, medical and electronics through advanced powder metallurgy technology, precision processing technology and customized services.
- **Global layout and supply chain integration**
  Major companies build global production and sales networks through overseas investment, mergers and acquisitions, and cooperation to improve supply chain response speed and market coverage.

10.3.3 Competitive advantages and challenges

- **Chinese companies have**
  rich raw material supply guarantees and a complete industrial chain system, and have large-scale production and rapid delivery capabilities.
- **Technological barriers and brand influence**
  International leading companies have technological barriers in precision manufacturing, quality control and innovative applications, high brand awareness and strong customer stickiness.
- **Environmental policies and compliance pressures As**
  countries around the world raise their requirements for environmental protection and safety regulations, this increases compliance costs and production risks for companies.

10.3.4 Future Competition Trends

- **Innovation-driven development**
  companies will increase investment in research and development, promote the performance improvement of tungsten alloy materials and the application of new processes, and meet the diversified needs of the high-end market.

- **Green manufacturing and sustainable development**
  and environmental compliance will become important factors in corporate competition, and green production processes and circular economy models will gradually become popular.
- **Cross-industry cooperation and ecological construction**
  build comprehensive service capabilities through cooperation with upstream and downstream enterprises in the downstream industrial chain, and achieve synergy and win-win results in the industrial chain.

10.4 Product Upgrade Trends Driven by New Technologies

10.4.1 Advances in Powder Metallurgy Technology

As the core technology of tungsten alloy counterweight manufacturing, powder metallurgy has made significant technological breakthroughs in recent years. The preparation and application of nano-scale ultrafine powders have improved the density and mechanical properties of tungsten alloys. The development of high temperature and high pressure sintering technology has promoted the uniformity and stability of the counterweight structure, meeting the stringent requirements of aerospace and high-precision fields.

10.4.2 Application of Additive Manufacturing (3D Printing) Technology

Additive manufacturing technology is gradually becoming popular in the production of tungsten alloy counterweights, especially for the manufacture of complex structures and customized counterweights. 3D printing not only shortens the R&D cycle, but also enables the realization of complex geometric shapes that are difficult to achieve with traditional processing, thereby increasing the freedom of product design and functional integration.

10.4.3 Intelligent Manufacturing and Automated Production

Combined with the concept of Industry 4.0, intelligent manufacturing technology is widely used in the production of tungsten alloy counterweights. Through the Internet of Things (IoT), big data analysis and intelligent robots, real-time monitoring, quality tracking and automated operation of the production process are achieved, greatly improving production efficiency and product consistency.

10.4.4 Surface Engineering Technology Innovation

Advanced surface treatment technologies, such as laser cladding, ion implantation and nano-coating, improve the wear resistance, corrosion resistance and fatigue life of tungsten alloy counterweights. Surface functionalization not only enhances material performance, but also gives the product specific electromagnetic shielding and thermal management functions.

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10.4.5 Multi-material composite counterweight technology

Multi-material composite technology combines tungsten alloy with lightweight and high-strength materials (such as titanium alloy and carbon fiber composite materials) to achieve a balance between high density and light weight. Through advanced bonding and mechanical bonding processes, the weight system is customized to meet the diverse performance requirements of different applications.

10.4.6 Green Manufacturing and Circular Economy Technologies

New technologies promote the transformation of tungsten alloy production to green manufacturing. The application of material recycling, low-energy smelting and environmentally friendly processes can reduce environmental burden, lower production costs and achieve sustainable use of resources.

The integration of these technologies drives tungsten alloy counterweight products to develop in the direction of high performance, high precision, multi-function and environmental protection, meeting the diverse demands for counterweight materials in future intelligent manufacturing and high-end equipment.

10.5 Strategic Position of Tungsten Alloy Counterweights in Future High-end Equipment

10.5.1 The Core Value of Tungsten Alloy Counterweights

Tungsten alloy has become the preferred material for high-end equipment counterweights due to its high density, high strength, high temperature resistance and excellent mechanical properties. In the fields of aircraft, satellites, precision instruments, advanced medical equipment, etc., tungsten alloy counterweights not only ensure the stability and accuracy of the equipment, but also play a key role in improving overall performance and safety.

10.5.2 Future Demand Driving Forces for High-end Equipment

- **improvement**
  of intelligence level of high-end equipment, higher requirements are put forward for the small size, high precision and multi-functional integration of counterweight materials. Tungsten alloy counterweights just meet these requirements.
- generation of equipment emphasizes **lightweight**
  design, but core components still require high-density counterweight materials to ensure performance balance. The combination of tungsten alloy and composite materials has become a trend.
- **Extreme Environment Adaptability**
  Aerospace and defense equipment are often in high temperature, high radiation and strong vibration environments. The excellent heat resistance and stability of tungsten alloy make it an irreplaceable strategic material.

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10.5.3 Strategic Advantages of Tungsten Alloy Counterweights

- **Material stability and reliability**
  Tungsten alloy has stable performance under various extreme conditions, ensuring the long-term reliable operation of high-end equipment and reducing maintenance costs and risks.
- **Technological innovation promotes strategic upgrading**
  of new tungsten alloy materials, intelligent manufacturing technology and composite materials, giving counterweights more functions and promoting the improvement of strategic position.
- **Supply Chain Security and National Strategic**
  Tungsten Resources As a strategic rare metal, ensuring the security of the tungsten alloy counterweight material supply chain is an important basis for ensuring the independent and controllable national high-end equipment.

10.5.4 Future Development Trends and Strategic Layout

- **In-depth integration of the industrial chain**
  will strengthen the deep integration of tungsten resource mining, material preparation, processing and manufacturing, and application development, build a complete industrial ecology, and enhance competitiveness.
- **Independent innovation and technological breakthroughs**
  : Increase R&D investment, break through high-performance tungsten alloy materials and manufacturing processes, and meet the diverse and highly complex needs of future equipment.
- **International Cooperation and Market Expansion**
  Actively participate in international high-end equipment manufacturing cooperation, expand the global market, and enhance the international influence of tungsten alloy counterweights.

tungsten alloy counterweights will continue to strengthen with the upgrading of equipment technology and the growth of market demand. In the future, tungsten alloy counterweights will play a more important role in many fields such as intelligent manufacturing, green environmental protection, and national defense security.

Appendix

Appendix 1 Specifications and performance parameters of common tungsten alloy counterweights

Product Type	Typical dimensions (mm)	Density (g/cm³)	Hardness (HV)	Tensile strength (MPa)	Remark
Micro weights	1×1×1 ~ 10×10×10	17.0 - 18.5	280 - 320	600 - 800	Used for precision instruments, gyroscope counterweights
Standard rectangular counterweight	20×20×5 ~ 100×50×20	17.5 - 18.3	300 - 350	700 - 900	Aerospace, automotive counterweights
Cylindrical counterweight	Diameter 550, length 1000	17.0 - 18.4	280 - 330	650 - 850	Vibration control of construction machinery and equipment
Customized complex shape counterweight	Customized according to customer needs	17.0 - 18.5	280 - 360	600 - 900	High-end electronic and medical equipment counterweights
Ultra-fine microstructure counterweight	Micron size, special customization	17.8 - 18.5	300 - 370	700 - 950	Mobile phone anti-shake module (OIS)

Typical tungsten alloy performance indicators

- **Density** : The high density of tungsten alloy weights is its core advantage, usually between 17.0~18.5 g/cm³, and the specific value is affected by the alloy composition and sintering process.
- **Hardness (HV)** : The Vickers hardness range reflects the wear resistance and mechanical strength of the material. Tungsten alloy has a higher hardness and is suitable for high-intensity load environments.
- **Tensile strength** : reflects the overall mechanical properties of the material and ensures the structural stability of the counterweight during use.

Appendix II Comparison Table of International and Chinese Tungsten Alloy Standards

Standard Category	International standards (ISO/ASTM/AMS, etc.)	Chinese standards (GB/GJB/HB, etc.)	Standard name/Scope of application
Basic Tungsten Material Standards	ISO 6841	GB/T 34515	Tungsten alloy material classification and grade specification
	ASTM B777	GB/T 24178	Technical Specifications and Mechanical Properties Test Methods of Heavy Tungsten Alloys
	AMS 7725	GJB 2538	for military tungsten-based heavy alloy materials

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Powder Metallurgy Product Standards	ISO 4499	GB/T 16522	Cemented Carbide Microstructure Rating Method
	ISO 4498	GB/T 4297	Determination method of density and porosity of powder metallurgy products
	ASTM B311	GB/T 5169	Test method for compressive strength of powder metallurgy materials
Machining and Inspection	ISO 2768	GB/T 1804	Tolerance and dimensional limit standards
	ASTM E8	GB/T 228.1	Metal Tensile Test Standards
	ASTM E384	GB/T 4340.1	Vickers hardness test method
Surface treatment and environmental protection	ISO 9227	GB/T 10125	Salt spray test standards
	RoHS / REACH (EU regulations)	GB/T 26572 / SJ/T 11363	Requirements for the restriction of the use of hazardous substances (environmental compliance)
Aerospace and military	AMS-T-21014	HB 5336 / GJB 5978	Tungsten alloy standard for aircraft structure, suitable for aviation and military counterweights
	MIL-T-21014E	GJB 1538	Military Tungsten Alloy Counterweights

Additional Notes:

- **ASTM B777 vs GB/T 24178** : It is one of the most commonly used standards for tungsten alloy weights, covering Class 1-4 high-density tungsten alloys of different density levels, and is widely used in aerospace, medical, sports equipment and other fields.
- **REACH & RoHS and GB/T 26572** : In the application of tungsten alloy counterweights, special attention should be paid to whether it contains restricted substances such as lead, cadmium, and mercury. Chinese companies must comply with such environmental regulations when exporting to the European and American markets.
- **GJB series standards** : specific requirements for the military industry, widely used in inertial counterweights, weapon systems and national defense equipment.

Appendix III Commonly used equipment and process parameters for preparing tungsten alloy counterweights

1. Powder preparation equipment and parameters

Device Name	Key Features	Typical parameter range	Key points of the process
Gas atomization device	Preparation of spherical tungsten powder	Powder size 0.5–20 μm , sphericity > 95%	Control argon pressure, droplet temperature and nozzle structure
Planetary ball mill	Mixed/refined alloy powder	Speed 200–600 rpm, time 2–24 hours	Need to maintain low oxygen environment to prevent oxidation
Vibration screening equipment	Powder particle size classification	Screen 20–500 mesh	Powder particle size consistency directly affects subsequent density

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2. Forming equipment and parameters

Device Name	Forming method	Common forming parameters	Applicable product types
Cold Isostatic Press (CIP)	High pressure uniform forming	Pressure 100–400 MPa, time 1–5 minutes	Suitable for complex shapes and high density counterweights
One-way press	Mold pressing	Pressure 50–200 MPa	Small batch rectangular/cylindrical counterweights
Injection molding equipment (MIM)	Micro precision weight forming	Injection temperature 150–200°C, holding pressure 5–10 seconds	Mobile phone OIS module, micro counterweight

3. Sintering equipment and parameters

Device Name	Sintering type	Common process parameters	Process characteristics
Vacuum sintering furnace	High temperature solid phase sintering	Temperature 1500–1800°C, vacuum < 10^{-3} Pa	Maintain alloy purity and density, suitable for high-performance products
Hot Isostatic Pressing (HIP)	Sintering + densification	Temperature 1300–1600°C, pressure 100–200 MPa	Eliminate internal porosity and improve mechanical properties
Hydrogen protection sintering furnace	Reducing atmosphere sintering	Temperature 1400–1600°C, H_2 flow rate 0.5–2 m^3/h	Reduce oxygen content and improve electrical performance

4. Precision machining equipment and parameters

Device Name	Processing method	Accuracy/parameter range	Application Examples
CNC Milling	Plane/curved surface precision machining	Processing accuracy ±5 μm , surface roughness Ra<0.8 μm	Aviation weights, MRI weights
Wire cutting machine	Complex contour cutting	Wire diameter φ0.1–0.2 mm, cutting accuracy ±3 μm	Radiotherapy equipment mechanical arm counterweight, mirror frame counterweight
Ultrasonic grinding machine	Ultra-fine finishing and chamfering	Sub-micron precision can be achieved, surface Ra<0.2 μm	MEMS/OIS module counterweight, gyroscope counterweight

5. Surface treatment equipment and parameters

Device Name	Surface treatment	Process parameter range	Process effect description
Alumina sandblasting machine	Roughening/cleaning surfaces	Spray pressure 0.3–0.6 MPa, particle size 30–100 μm	Enhance surface bonding
Vacuum coating equipment	Hard protective coating	TiN / TaN film thickness 0.2–2 μm , temperature 150–250°C	Improve wear resistance and corrosion resistance
Electrochemical polishing device	Improve surface finish	Voltage 10–20 V, time 5–15 minutes	Used in high-end medical and electronic precision weighting

6. Quality inspection equipment and control parameters

Testing equipment	Test items	Test range and accuracy	Usage
Helium mass spectrometer leak detector	Density and sealing	Detection limit <10^{-9} Pa · m^3 / s	High reliability military/aerospace product testing

X-ray CT scanner	Internal defects and pore identification	Resolution <10 µm	Quality Control of Complex Counterweights
Coordinate Measuring Machine (CMM)	Dimensional and geometrical tolerances	Measurement accuracy ±1~2 µm	Finished product inspection of precision counterweights
Laser Particle Size Analyzer	Powder particle size distribution	Particle size range 0.1–100 µm , error <±3%	Raw material powder quality determination

Appendix IV: Glossary and Explanation of Abbreviations

Abbreviations/Terms	**English full name / Chinese meaning**	**Description and application scenarios**
W	Tungsten	High melting point and high density metals are the core raw materials of tungsten alloy counterweights.
CIP	Cold Isostatic Pressing	High-pressure liquid is used to evenly press the powder from all directions to improve the density of the green body.
HIP	Hot Isostatic Pressing	High temperature and high pressure densification technology significantly improves material strength and structural consistency.
MIM	Metal Injection Molding	Suitable for batch manufacturing of complex micro tungsten alloy parts, such as mobile phone lens OIS weight.
OIS	Optical Image Stabilization	Tungsten alloy micro-weight system in the anti-shake structure of mobile phone cameras .
CNC	Computer Numerical Control / CNC Machining Center	Used for milling, drilling and other machining of high-precision tungsten alloy parts.
EDM	Electrical Discharge Machining	This method is commonly used when machining complex shapes of high- hardness materials such as tungsten .
ISO	International Organization for Standardization	that develops standards for tungsten alloy materials, processing, and environmental protection.
ASTM	American Society for Testing and Materials	tungsten alloy materials and mechanical properties testing.
GB	GuoBiao / China National Standard	Technical standards for common materials and processes in China.
JB	Guojia Junyong Biaozhun / National Military Standards	Used for quality control and testing requirements of military tungsten alloy counterweights.
RoHS	Restriction of Hazardous Substances	To limit the use of harmful elements such as lead and cadmium in electronic devices, tungsten alloy is often used as a non-toxic substitute.

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REACH	, Evaluation , Authorisation and Restriction of Chemicals	Exporting companies must comply with EU regulations on the use of chemical substances.
FEA	Finite Element Analysis	A commonly used simulation tool for simulating the structural stress and dynamic balance of counterweight systems.
CMM	Coordinate Measuring Machine	for testing geometric dimensions and form and position tolerances of tungsten alloy parts.
TiN	Titanium Nitride	Surface coating materials can improve the wear resistance and corrosion resistance of tungsten alloy surface.
W-Ni-Fe / W- Ni-Cu	Tungsten-Nickel-Iron / Tungsten-Nickel-Copper	Common tungsten-based high- density alloy formula, suitable for counterweights in aerospace, military industry, medical and other fields.
Density	g/cm^3	tungsten alloy counterweights determine its ability to have a small volume and high mass.
Densification	Material structure without internal pores or voids	The mechanical strength and service life of the counterweight are important indicators of the manufacturing quality of tungsten alloy.
Micromachining	Processing technology with micron or nanometer precision	Aimed at the precision manufacturing of micro-weights such as OIS, MEMS systems and other devices.

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