

What Is Tungsten Nickel Iron Alloy

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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CTIA GROUP LTD
Tungsten Nickel Iron Alloy Introduction

1. Overview of Tungsten Nickel Iron Alloy

Tungsten-nickel-iron alloy is a high-density material with tungsten as the primary component and nickel and iron added as binder phases. Known for its excellent physical and chemical properties, it is widely used in aerospace, military, medical, nuclear industries, and civilian fields. CTIA GROUP LTD offers tungsten-nickel-iron alloy products, including alloy rods, counterweights, radiation shields, and phone vibrators, tailored for various applications.

2. Features of Tungsten Nickel Iron Alloy

High Density: Typically ranges from 16.5 to 18.75 g/cm³.

High Strength: Tensile strength ranges from 700 to 1000 MPa.

Other Characteristics: Exhibits strong radiation absorption, high thermal conductivity, low thermal expansion coefficient, good electrical conductivity, plasticity, weldability, and processability.

3. Tungsten-Nickel-Iron Alloy Grades

Grade	Class 1	Class 1	Class 2	Class 2	Class 3	Class 3	Class 4
Composition (%)	90W 7Ni3Fe	91W 6Ni3Fe	92W 5Ni3Fe	93W 4Ni3Fe	95W 3Ni2Fe	96W 3Ni1Fe	97W 2Ni1Fe
Density (g/cm ³)	17.1	17.25	17.50	17.60	18.10	18.30	18.50
Heat Treatment	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering
Tensile Strength (PSI)	900~1000		900~1100		920~1100		
Elongation (%)	18~29	17~27	16~26	16~24	10~22	8~20	6~13
Hardness (HRC)	24~28	25~29	25~29	26~30	27~32	28~34	28~36

4. Production Methods for Tungsten Nickel Iron Alloy

The powder metallurgy process involves first mixing tungsten powder, nickel powder, and iron powder; then ball milling and sieving; followed by shaping the mixed powder into blanks using hot pressing, hot isostatic pressing, or vacuum sintering techniques; and finally improving the alloy's microstructure and properties through heat treatments such as annealing or quenching.

5. Applications of Tungsten Nickel Iron Alloy

In the medical field, tungsten-nickel-iron alloy serves as radiation shields, radiation source containers, collimators, isotope containers, and syringe shields. In scientific research, tungsten alloy is used as heat sinks and for oil drilling and mineral resource exploration.

6. Purchasing Information

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Chapter 1 Basic Knowledge of Tungsten-Nickel-Iron Alloy

1.1 Definition of Tungsten Nickel Iron Alloy

Tungsten Nickel Iron Alloy is a high-density alloy material with tungsten as the main component and nickel and iron as the binder phase. It is usually classified as a high-density alloy. This alloy is widely used in aerospace, military, medical, nuclear industry and civilian fields due to its excellent physical and chemical properties. The definition of tungsten nickel iron alloy comes from its main constituent elements and their unique combination of properties: tungsten provides high density and high strength, and nickel and iron as binders enhance the toughness and machinability of the alloy.

Tungsten -nickel-iron alloy is usually between 16.5-18.75 g/cm³, which is close to the density of precious metals such as gold or platinum , so it is often used as a substitute material. Its main characteristics include high density, high temperature resistance, corrosion resistance and good machinability. Compared with other high-density materials, tungsten-nickel-iron alloy has a higher cost-effectiveness, especially in application scenarios that require high weight to be concentrated in a small volume, such as counterweights, radiation shielding materials and military armor-piercing projectiles.

Tungsten -nickel-iron alloy is usually completed through powder metallurgy process, which involves mixing high-purity tungsten powder, nickel powder and iron powder in a specific proportion, pressing and forming, and sintering at high temperature to form a dense alloy structure. During the sintering process, nickel and iron form a liquid phase, which promotes the bonding of tungsten particles, thus giving the alloy excellent mechanical properties. The composition ratio of tungsten -nickel-iron alloy can be adjusted according to specific uses, such as increasing the proportion of nickel to improve toughness, or adjusting the iron content to optimize cost.

From the application perspective, tungsten-nickel-iron alloy is widely used in counterweight components in the aerospace field due to its high density and high strength, such as the balance weight of an aircraft or the rotor counterweight of a helicopter. In addition, in the medical field, tungsten-nickel-iron alloy is used to manufacture X-ray or gamma-ray protection equipment due to its excellent radiation shielding performance. In the military field, tungsten-nickel-iron alloy is often used to manufacture armor-piercing cores because of its high density and high hardness, which can effectively penetrate armored targets. In short, the definition of tungsten-nickel-iron alloy not only covers its chemical composition, but also includes its unique value in a variety of high-end applications.

1.2 Composition of tungsten-nickel-iron alloy

Tungsten -nickel-iron alloy mainly includes three elements: tungsten (W), nickel (Ni) and iron (Fe). Among them, tungsten content usually dominates, generally accounting for 85%-95%, while nickel and iron, as bonding phases, account for 5%-15% respectively. In addition, depending on the specific use, trace amounts of other elements such as copper, cobalt or molybdenum may be added to the alloy to further optimize the performance. The composition ratio of tungsten -nickel-iron alloy directly affects its

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physical properties (such as density, hardness and toughness) and processing performance. Therefore, in actual production, the proportion of each element needs to be precisely controlled according to application requirements.

Tungsten is the core component of the alloy, providing high density (19.25 g/cm^3) and high melting point (3410°C), making it an ideal choice for high-density alloys. Nickel, as the main binder, has good ductility and corrosion resistance, and can form a liquid phase during the sintering process to promote the bonding of tungsten particles, thereby improving the overall strength and toughness of the alloy. Iron further enhances the mechanical properties of the alloy while reducing production costs. The synergistic effect of nickel and iron enables tungsten -nickel-iron alloys to have good machinability and impact resistance while maintaining high density.

Tungsten -nickel-iron alloy is usually expressed in weight percentage. For example, the common 90W-7Ni-3Fe alloy means 90% tungsten, 7% nickel, and 3% iron. This ratio design can balance high density and mechanical properties and is suitable for a variety of application scenarios. It is worth noting that the ratio of nickel to iron will significantly affect the performance of the alloy: when the nickel content is higher, the alloy has better toughness and ductility; an increase in iron content may increase hardness, but may reduce corrosion resistance. Therefore, in actual production, the formula needs to be optimized according to specific uses.

The microstructure of tungsten -nickel-iron alloy consists of tungsten particles and nickel-iron matrix. Tungsten particles are usually nearly spherical or polygonal, embedded in the nickel-iron matrix to form a uniform composite structure. This structure gives the alloy excellent mechanical properties, such as high tensile strength (usually $800\text{-}1000 \text{ MPa}$) and appropriate ductility. In addition, the corrosion resistance and oxidation resistance of the alloy also benefit from the presence of nickel, enabling it to be used for a long time in harsh environments. In short, the composition design of tungsten-nickel-iron alloy is the key to its superior performance, which directly determines its wide application in high-performance fields.

1.2.1 Characteristics and functions of tungsten

Tungsten (element symbol W) is the most critical component in tungsten-nickel-iron alloy. Its unique physical and chemical properties provide the core performance of the alloy. Tungsten is a rare metal with an extremely high density (19.25 g/cm^3), close to the density of gold (19.32 g/cm^3), and is one of the densest metals in nature. This high density makes tungsten -nickel-iron alloy an ideal material for applications that require high weight to be concentrated in a small volume, such as aerospace counterweights or military armor-piercing cores.

Tungsten has an extremely high melting point of 3410°C , the highest of all metals, which gives tungsten-nickel-iron alloy excellent high temperature resistance, enabling it to maintain structural stability in high temperature environments. For example, in the aerospace field, tungsten-nickel-iron alloys are often used to manufacture counterweight components for turbine blades, which can withstand extreme conditions

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of high temperature and high-speed rotation. In addition, tungsten has an extremely high hardness (Mohs hardness of about 7.5), second only to diamond, which makes tungsten -nickel-iron alloy have excellent wear resistance and is suitable for manufacturing wear-resistant parts or high-strength tools.

Tungsten's chemical stability also provides important support for its role in alloys. Tungsten has good corrosion resistance to most acids and alkalis and can remain stable in harsh chemical environments. This makes tungsten -nickel-iron alloys perform well in radiation shielding applications in the nuclear industry and medical fields, such as for the manufacture of gamma-ray shields. Tungsten's low coefficient of thermal expansion (about $4.5 \times 10^{-6} / ^\circ \text{C}$) further enhances the dimensional stability of the alloy, allowing it to maintain precise geometry in environments with large temperature changes.

In tungsten-nickel-iron alloy, tungsten is evenly distributed in the nickel-iron matrix in the form of fine particles, forming a high-density composite structure. The high hardness and high density of tungsten particles provide the main mechanical properties and weight characteristics for the alloy, while the nickel-iron matrix tightly combines the tungsten particles through liquid phase sintering, making up for the shortcomings of pure tungsten material brittleness and difficulty in processing. This synergistic effect enables tungsten -nickel-iron alloy to have sufficient toughness and machinability while maintaining high density.

The role of tungsten in the alloy is also reflected in its radiation shielding ability. Due to its high atomic number ($Z=74$), tungsten can effectively absorb high-energy radiation, such as X-rays and gamma rays. This makes tungsten -nickel-iron alloys important in medical equipment (such as CT machine shields) and the nuclear industry (such as radioactive waste containers). In addition, tungsten's thermal conductivity (about $173 \text{ W/m}\cdot\text{K}$) and electrical conductivity also provide additional advantages for the alloy in certain special applications, such as use as electrode materials or heat sinks.

1.2.2 Characteristics and functions of nickel

Nickel (element symbol Ni) is an important bonding phase element in tungsten-nickel-iron alloy, usually accounting for 5%-10% of the total mass of the alloy, and plays a key role in optimizing the performance of the alloy. Nickel is a silvery-white transition metal with good ductility, toughness and corrosion resistance. Its density is 8.91 g/cm^3 and its melting point is 1455°C . The addition of nickel significantly improves the machining and mechanical properties of tungsten-nickel-iron alloy, making it have sufficient toughness and impact resistance while maintaining high density, overcoming the shortcomings of pure tungsten material, which is brittle and difficult to process.

In the powder metallurgy production process of tungsten-nickel-iron alloy, the main role of nickel is reflected in the liquid phase sintering stage. Since the melting point of nickel is much lower than that of tungsten (3410°C), during high-temperature sintering, nickel will first melt to form a liquid phase, fill the gaps between tungsten particles, and promote the rearrangement and bonding of tungsten particles through capillary action. This liquid phase sintering mechanism significantly improves the density of the alloy (usually close to 99% of the theoretical density), thereby enhancing the strength and toughness

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of the alloy. The matrix formed by nickel firmly wraps the high-hardness tungsten particles to form a uniform composite structure, enabling the alloy to maintain structural integrity under high stress environments.

The chemical stability of nickel is another important characteristic of tungsten-nickel-iron alloy. Nickel has excellent corrosion resistance to most acid, alkali and oxidizing environments, and can effectively resist the erosion of moisture, salt spray and other corrosive media. This allows the application of tungsten -nickel-iron alloy to be expanded in harsh environments, such as in marine engineering or chemical industry as corrosion-resistant counterweights. In addition, the anti-oxidation property of nickel also provides protection for the alloy in high temperature environments, extending the service life of the material.

From the perspective of mechanical properties, the ductility and toughness of nickel significantly improve the impact resistance and fracture resistance of tungsten-nickel-iron alloys. Pure tungsten materials are prone to fracture when subjected to impact or cyclic stress due to their high hardness and brittleness, and the presence of nickel gives the alloy a certain degree of plastic deformation ability. For example, the tensile strength of 90W-7Ni-3Fe alloy can reach 800-1000 MPa, and it has an elongation of about 10%-20%, which makes it perform well in high-stress applications such as aerospace counterweights or military armor-piercing cores.

Nickel also has a certain effect on the magnetic properties of the alloy. Nickel is a ferromagnetic material, and its addition makes the tungsten-nickel-iron alloy exhibit weak magnetism, which has potential advantages in certain specific applications (such as scenarios requiring magnetic shielding or magnetic positioning). However, the nickel content needs to be precisely controlled, because too high a nickel ratio may cause the alloy density to decrease, affecting its high specific gravity characteristics. In addition, the cost of nickel is relatively high, so it is necessary to balance performance and economy in actual production.

In short, the role of nickel in tungsten -nickel-iron alloy is mainly reflected in improving mechanical properties, promoting sintering process, enhancing corrosion resistance and providing certain magnetic properties. The synergistic effect of nickel, tungsten and iron enables the alloy to achieve an ideal balance between high density, high strength and machinability, becoming an indispensable material in aerospace, military and medical fields.

1.2.3 Characteristics and functions of iron

Iron (element symbol Fe) is another key bonding phase element in tungsten-nickel-iron alloy, usually accounting for 2%-5% of the alloy mass. With a density of 7.87 g/cm³ and a melting point of 1538°C, iron's physical and chemical properties provide important performance supplements for the alloy. The addition of iron not only reduces production costs, but also plays an important role in enhancing the mechanical properties of the alloy, optimizing the microstructure, and adjusting the magnetic properties, enabling tungsten-nickel-iron alloy to meet diverse application requirements. In the manufacturing

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process of tungsten-nickel-iron alloy, iron and nickel act as bonding phases together and participate in the liquid phase sintering process. Since the melting point of iron is lower than that of tungsten, iron and nickel melt together during sintering to form a liquid phase matrix, which promotes the bonding and rearrangement of tungsten particles. The presence of iron can refine the microstructure of the alloy and make the tungsten particles more evenly distributed, thereby improving the overall strength and toughness of the alloy. For example, in 90W-7Ni-3Fe alloy, the addition of iron makes the microstructure of the alloy more compact, and the tensile strength and hardness are significantly improved, which is suitable for manufacturing high-performance counterweights or armor-piercing cores.

The mechanical properties of iron cannot be ignored in reinforcing tungsten-nickel-iron alloys. Iron has high hardness and strength (Mohs hardness of about 4-5), and its addition increases the overall hardness of the alloy, making it perform well in applications that require wear resistance or impact resistance. Compared with nickel, iron has lower ductility, but its higher hardness makes up for this deficiency, allowing the alloy to withstand greater mechanical loads in high-stress environments. For example, in the military field, tungsten-nickel-iron alloys are used as armor-piercing cores due to their high hardness and high density, which can effectively penetrate armored targets.

The economics of iron is an important factor in its use in tungsten-nickel-iron alloys. Compared to nickel, iron has a significantly lower cost, and the use of partial substitution for nickel can effectively reduce the production cost of the alloy without significantly sacrificing performance. This makes tungsten-nickel-iron alloys more competitive in civilian areas such as sports equipment weights or industrial tools. However, iron has poor corrosion resistance and is easily oxidized in humid or acidic environments, so it is necessary to rely on the corrosion resistance of nickel to make up for this shortcoming. In actual production, the ratio of nickel to iron needs to be precisely optimized to balance corrosion resistance and cost.

The ferromagnetism of iron also brings certain magnetic properties to tungsten-nickel-iron alloy. Similar to nickel, the addition of iron makes the alloy weakly magnetic, which is advantageous in certain applications that require magnetic response, such as in electromagnetic devices or magnetic positioning systems. In addition, the addition of iron can also fine-tune the thermal expansion coefficient and thermal conductivity of the alloy, so that it maintains stable performance in high temperature or thermal cycle environments.

It should be noted that an increase in iron content may have a negative impact on the properties of the alloy. For example, too high an iron ratio may lead to a decrease in the corrosion resistance of the alloy, or induce unnecessary phase changes during high-temperature sintering, affecting the stability of the microstructure. Therefore, in the design of tungsten-nickel-iron alloys, the iron content is usually controlled at a lower ratio (such as 2%-5%) to ensure a balance of performance.

1.3 Historical Background and Development of Tungsten-Nickel-Iron Alloy

As a high-density alloy material, the historical background and development of tungsten-nickel-iron

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alloy are closely related to the progress of modern industrial technology. Since the unique properties of tungsten were recognized in the late 19th century, tungsten-based alloys have gradually become the focus of research in the field of high-performance materials. By combining the high density of tungsten with the bonding properties of nickel and iron, tungsten -nickel- iron alloy overcomes the processing difficulties of pure tungsten materials and gradually occupies an important position in the fields of aerospace, military, medical and industrial fields. Its development process not only reflects the progress of materials science, but also reflects the growing demand of mankind for high-performance materials.

Tungsten -nickel-iron alloys benefited from the maturity of powder metallurgy technology, especially the breakthrough in liquid phase sintering technology, which enabled large-scale production in the mid-20th century. With the acceleration of global industrialization, especially the demand for high-performance materials during World War II, the development and application of tungsten-nickel-iron alloys have been rapidly promoted. From the initial military field to the later civilian and medical fields, the application scope of tungsten-nickel-iron alloys has been continuously expanded, and its performance has been continuously optimized. The following will discuss in detail the discovery of tungsten -nickel-iron alloys and their early applications and technological advances.

1.3.1 Discovery of Tungsten-Nickel-Iron Alloy

Tungsten -nickel-iron alloy is closely related to the study of the characteristics of tungsten and the development of powder metallurgy technology. As a rare metal with high density and high melting point, tungsten attracted the attention of scientists as early as the end of the 18th century. In 1783, Spanish chemists, the Eluad brothers, separated tungsten from tungstic acid for the first time and confirmed its high density (19.25 g/cm^3) and high melting point (3410°C). However, due to the brittleness and difficulty of processing tungsten, the early application of tungsten was mainly limited to pure tungsten or simple tungsten compounds, such as tungsten filaments used in light bulb manufacturing.

Tungsten -nickel-iron alloy occurred in the early 20th century with the rise of powder metallurgy technology. From the late 19th century to the early 20th century, materials scientists began to explore improving the processing properties of tungsten by adding low- melting-point metals such as nickel and iron. Nickel and iron were selected as bonding phases because of their good ductility and low melting point (nickel 1455°C , iron 1538°C), which can form a liquid phase during high-temperature sintering and wrap the high-melting- point tungsten particles to form a dense alloy structure. The prototype of this method first appeared in the 1920s, when researchers tried to prepare tungsten-based composite materials through powder metallurgy to meet the needs of industry and military fields.

Tungsten -nickel-iron alloy began in the 1930s, mainly driven by military needs. On the eve of World War II, the demand for high-performance armor-piercing materials in various countries surged, and the high density and high hardness of tungsten made it an ideal choice for armor-piercing projectile cores. However, the brittleness of pure tungsten makes it difficult to process into complex shapes, limiting its application. Researchers have found that by adding nickel and iron, the toughness and machinability of tungsten-based materials can be significantly improved. In the late 1930s , scientific research institutions

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in the United States and Germany almost simultaneously developed alloy formulas with tungsten as the main body and nickel and iron as the bonding phase, with a typical ratio of 90W-7Ni-3Fe. The emergence of this formula marks the official birth of tungsten-nickel-iron alloy.

The discovery of nickel-iron alloy also benefited from the in-depth understanding of the liquid phase sintering mechanism. During the sintering process, the liquid phase of nickel and iron can effectively fill the gaps between tungsten particles, reduce porosity, and improve the density and mechanical properties of the alloy. This technological breakthrough laid the foundation for the industrial production of tungsten-nickel-iron alloy. In the 1940s, with the improvement of powder metallurgy equipment and processes, the production efficiency and quality of tungsten-nickel-iron alloy were further improved, and its application areas also expanded from military industry to civilian and medical fields. In short, the discovery of tungsten-nickel-iron alloy is the comprehensive result of tungsten property research and powder metallurgy technology development, which has opened up a new path for the application of modern high-performance materials.

1.3.2 Early Applications and Technological Advances

tungsten -nickel-iron alloys were mainly concentrated in the military industry, especially during World War II (1939-1945). Due to its high density and high hardness, tungsten-nickel-iron alloys are widely used in the manufacture of armor-piercing ammunition cores to meet the protection needs of tanks and armored vehicles. Compared with traditional steel cores, tungsten-nickel-iron alloy cores can provide greater kinetic energy in a smaller volume and effectively penetrate heavy armor. This application has greatly promoted the research and development and production of tungsten-nickel-iron alloys, prompting countries to invest a lot of resources to optimize their formulations and manufacturing processes.

In terms of technology, the production of early tungsten -nickel-iron alloys mainly relied on powder metallurgy processes, including three main steps: mixing, pressing and sintering. The sintering technology in the 1940s was able to achieve a higher density, but there were still some problems, such as uneven distribution of tungsten particles and difficult to control sintering shrinkage. In order to solve these problems, researchers have developed more advanced equipment, such as vacuum sintering furnaces and hot isostatic pressing (HIP) technology. These technologies are capable of sintering at higher temperatures and pressures, further improving the density and mechanical properties of the alloy. For example, hot isostatic pressing technology significantly reduces the porosity inside the alloy by sintering under isotropic pressure, so that its tensile strength reaches 800-1000 MPa and its elongation reaches 10%-20%.

In terms of formula design, the typical ratio of early tungsten -nickel-iron alloys was 90W-7Ni-3Fe, but as application requirements diversified, researchers began to adjust the ratio of nickel and iron to optimize specific properties. For example, increasing the nickel content can improve the toughness of the alloy, making it suitable for parts that need to be impact-resistant; increasing the iron content can reduce costs and is suitable for large-scale production in the civilian field. In addition, the addition of trace elements (such as copper or cobalt) has also begun to be explored to further improve the corrosion

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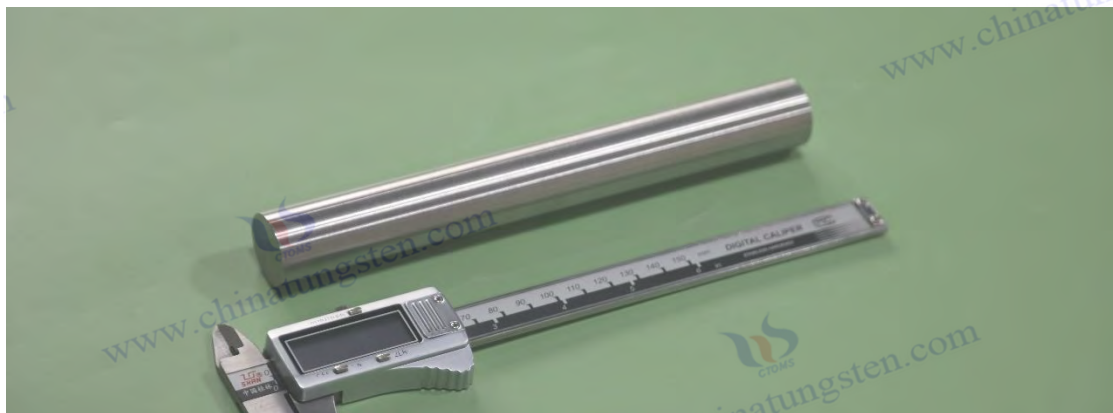
resistance or magnetic properties of the alloy.

In the 1950s, with the rapid development of the aerospace industry, the application of tungsten-nickel-iron alloys expanded to the field of counterweight components. Due to its high density (16.5-18.75 g/cm³), tungsten -nickel-iron alloys are used to manufacture balance weights for aircraft and helicopters, such as aileron counterweights and rotor balance devices. These components need to provide sufficient weight in a limited space, while requiring the material to have good mechanical properties and environmental adaptability. The corrosion resistance and dimensional stability of tungsten -nickel-iron alloys make it an ideal choice.

In the medical field, the radiation shielding properties of tungsten-nickel-iron alloys began to attract attention in the 1960s. Due to its high atomic number ($Z=74$), tungsten can effectively absorb X-rays and gamma rays, so it is used to manufacture protective covers for medical equipment and radiation shielding containers for the nuclear industry. Compared with traditional lead shielding materials, tungsten-nickel-iron alloys have higher density and better mechanical strength, can achieve the same shielding effect at a thinner thickness, and are more environmentally friendly.

Technological progress is also reflected in the improvement of alloy processing technology. The early mechanical processing of tungsten -nickel-iron alloys was difficult, especially in the manufacture of complex shapes. In the 1970s, the introduction of numerical control machining (CNC) and electrical discharge machining (EDM) technology significantly improved the machining accuracy and efficiency of the alloy, enabling it to be processed into more complex geometric shapes to meet the high-precision requirements of the aerospace and medical fields.

In short, the early application of tungsten-nickel-iron alloy was mainly in the military industry, and then expanded to the aerospace and medical fields. Its development benefited from the continuous progress of powder metallurgy, sintering technology and processing technology. These technological breakthroughs not only improved the performance and production efficiency of the alloy, but also promoted its wide application in many fields, laying an important foundation for the development of modern high-performance materials.



CTIA GROUP LTD Tungsten Nickel Iron Alloy Picture

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Chapter 2 Physical and Chemical Properties of Tungsten-Nickel-Iron Alloy

2.1 Density and mechanical properties of tungsten-nickel-iron alloy

Tungsten -nickel-iron alloys play an important role in many high-performance applications due to their excellent physical and mechanical properties. Their high density, excellent tensile strength and appropriate toughness make them ideal materials for aerospace, military, medical and industrial fields. The density of tungsten -nickel-iron alloys is usually between 16.5-18.75 g/cm³, close to the density of precious metals such as gold or platinum, while their mechanical properties are optimized by the synergy of tungsten's high hardness and nickel and iron binder phases. The following will discuss its high density characteristics as well as tensile strength and toughness in detail.

2.1.1 High-density characteristics

Tungsten -nickel-iron alloy is one of its most notable physical properties, mainly due to the high density of tungsten (19.25 g/cm³). As the main component of the alloy, the content of tungsten is usually between 85% and 95%, making the overall density of the alloy much higher than that of ordinary metal materials such as steel (7.85 g/cm³) or aluminum (2.7 g/cm³). By adjusting the ratio of nickel and iron, the density of tungsten-nickel-iron alloy can be precisely controlled in the range of 16.5-18.75 g/cm³ to meet the needs of different applications. For example, the density of 90W-7Ni-3Fe alloy is about 17.0 g/cm³, while the density of 95W-4Ni-1Fe alloy with a higher tungsten content can be close to 18.5 g/cm³.

The high density makes tungsten nickel iron alloy perform well in applications that require concentrated weight in a small volume. In the aerospace field, tungsten nickel iron alloy is often used to manufacture counterweight components for aircraft and helicopters, such as aileron balance weights or rotor counterweights. These components require sufficient mass in a limited space to ensure the stability and balance of the aircraft. Compared with traditional materials such as lead, tungsten nickel iron alloy not only has a higher density, but also has better mechanical strength and environmental stability, avoiding the toxicity and softness defects of lead.

In the military industry, the high density property gives tungsten -nickel-iron alloy excellent kinetic energy penetration ability. For example, the armor-piercing core uses the high density of tungsten -nickel-iron alloy to concentrate energy on a small area during high-speed impact, thereby effectively penetrating armored targets. In addition, the high density also makes it have important applications in the field of radiation shielding. The high atomic number of tungsten (Z=74) enables it to effectively absorb high-energy radiation such as X-rays and gamma rays, so tungsten -nickel-iron alloy is widely used as shielding material in medical equipment (such as CT machine protective covers) and nuclear industry (such as radioactive waste containers). Compared with lead, tungsten-nickel-iron alloy can achieve the same shielding effect at a thinner thickness, thereby reducing the size of the equipment.

Tungsten -nickel-iron alloy is also closely related to its microstructure. During the powder metallurgy production process, liquid phase sintering technology allows nickel and iron to form a matrix, tightly

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wrapping the tungsten particles and reducing the porosity, so that the density of the alloy is close to the theoretical value (more than 99%). This high density ensures the dimensional stability of the alloy under high stress or high temperature environments and avoids performance degradation caused by porosity. In addition, the low thermal expansion coefficient of tungsten-nickel-iron alloy (about $4.5-5.5 \times 10^{-6} / ^\circ \text{C}$) further enhances its stability in temperature-changing environments, giving it an advantage in precision instruments and high-temperature applications.

2.1.2 Tensile strength and toughness

Tungsten -nickel-iron alloys are the core of their mechanical properties, determining their reliability and application range in high-stress environments. The high hardness and strength of tungsten provide the basis for the alloy, while nickel and iron as bonding phases significantly improve the toughness and fracture resistance of the alloy. The tensile strength of a typical tungsten-nickel-iron alloy (such as 90W-7Ni-3Fe) is between 800-1000 MPa, and the elongation is about 10%-20%, which enables it to have a certain plastic deformation ability while maintaining high strength.

Tensile strength is the ability of WNiFe alloy to withstand tensile stress without breaking. During the powder metallurgy process, liquid phase sintering allows nickel and iron to form a uniform matrix that firmly binds the high-hardness tungsten particles. This composite structure enables the alloy to maintain structural integrity in high-stress environments. For example, in the aerospace field, WNiFe alloy is used to manufacture counterweight components for turbine blades, which are subject to huge tensile stresses caused by high-speed rotation and vibration. The high tensile strength of the alloy ensures that it will not fail under extreme conditions.

Toughness is another important characteristic of tungsten-nickel-iron alloy, which makes up for the brittle defect of pure tungsten material. Pure tungsten is prone to brittle fracture when subjected to impact or cyclic stress due to its high hardness and crystal structure characteristics. The ductility of nickel and the strength of iron form a synergistic effect in the alloy, enabling tungsten-nickel-iron alloy to absorb energy under impact or fatigue conditions and avoid sudden fracture. For example, in the application of military armor-piercing cores, tungsten-nickel-iron alloy needs to maintain structural integrity under high-speed impact, and its moderate toughness enables it to resist crack propagation caused by impact.

The ratio of nickel to iron has a significant effect on the tensile strength and toughness of the alloy. A higher nickel content (such as 7%-10%) can enhance the ductility and toughness of the alloy, making it more suitable for applications that require impact resistance; while increasing the iron content (such as 3%-5%) can increase the hardness and strength, but may slightly reduce toughness. Therefore, in actual production, the formula needs to be optimized according to specific uses. For example, the 90W-7Ni-3Fe alloy achieves a good balance between strength and toughness and is widely used in counterweights and military components; while alloys with higher tungsten content (such as 95W-4Ni-1Fe) focus more on strength and are suitable for scenarios requiring extremely high hardness.

The microstructure of tungsten -nickel-iron alloy also has an important influence on its mechanical properties. The size and distribution uniformity of tungsten particles directly determine the strength and

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toughness of the alloy. Smaller tungsten particles (usually in the range of 10-50 microns) and uniform matrix distribution can reduce stress concentration and improve tensile strength and fracture resistance. In addition, heat treatment and processing techniques (such as hot isostatic pressing) can further optimize the microstructure of the alloy, eliminate internal defects, and thus improve its mechanical properties.

2.1.3 Hardness and wear resistance

Tungsten -nickel-iron alloy are important components of its mechanical properties, enabling it to perform well in high-stress, high-wear environments. Hardness reflects the material's ability to resist deformation and scratches, while wear resistance determines the material's service life under friction or abrasive conditions. The high hardness and excellent wear resistance of tungsten -nickel-iron alloy are mainly due to the high hardness of tungsten (Mohs hardness of about 7.5) and the synergistic effect of nickel and iron bonding phases, making it widely used in scenarios that require wear resistance, such as military armor-piercing cores, industrial tools, and aerospace components.

Tungsten -nickel-iron alloys is usually between 250-400 Vickers hardness (HV), depending on the tungsten content and microstructure. For example, the hardness of 90W-7Ni-3Fe alloy is about 300 HV, while the hardness of 95W-4Ni-1Fe alloy with a higher tungsten content can reach 350-400 HV. The high hardness of tungsten provides the basis for the alloy, while the matrix formed by nickel and iron tightly combines the tungsten particles through liquid phase sintering, reducing micro defects, thereby further enhancing the overall hardness. This high hardness enables the alloy to resist plastic deformation caused by external forces, and is particularly suitable for manufacturing parts that require high strength and deformation resistance, such as armor-piercing cores or high-precision counterweights.

Wear resistance is another key property of WNiFe alloy, which comes from its high hardness and dense microstructure. In friction or abrasive environments, the high hardness of tungsten particles can effectively resist surface wear, while the toughness of the nickel-iron matrix prevents the material from cracking or flaking due to wear. For example, in the industrial field, WNiFe alloy is often used to manufacture wear-resistant parts of molds or cutting tools, which can maintain a long service life under high loads and repeated friction conditions. In addition, the alloy's low coefficient of friction (thanks to the surface properties of nickel) further improves its wear resistance and reduces wear on contact surfaces. tungsten -nickel-iron alloy is also closely related to its production process. Liquid phase sintering and hot isostatic pressing (HIP) technology in powder metallurgy can significantly improve the density of the alloy, reduce internal pores and microcracks, and thus enhance wear resistance. In addition, the size and distribution of tungsten particles have an important influence on wear resistance. Smaller tungsten particles (10-50 microns) can form a more uniform structure, reduce stress concentration, and thus improve wear resistance. In some applications, surface treatment (such as carburizing or coating) can further improve the wear resistance of the alloy, making it adaptable to more demanding working environments.

The balance between hardness and wear resistance is a key consideration in the design of tungsten-nickel-iron alloys. Too high a hardness may lead to a decrease in toughness, making the alloy susceptible to

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brittle fracture under impact conditions. Therefore, the ratio of nickel and iron needs to be precisely controlled to achieve the best balance between hardness and toughness. For example, increasing the nickel content can improve toughness, which is suitable for wear-resistant parts that need to resist impact; while increasing the iron content can increase hardness, which is suitable for high-wear scenarios. In short, the high hardness and wear resistance of tungsten-nickel-iron alloys give it irreplaceable advantages in a variety of high-performance applications.

2.2 Thermal properties of tungsten-nickel-iron alloy

Tungsten -nickel-iron alloy are its important characteristics in high temperature and thermal cycle environments, which directly affect its application in aerospace, military and industrial fields. Thermal properties include melting point, thermal stability, thermal conductivity and thermal expansion coefficient, among which the high melting point and excellent thermal stability of tungsten provide the alloy with reliability under extreme temperature conditions, while the addition of nickel and iron optimizes the balance between the thermal and mechanical properties of the alloy.

2.2.1 Melting point and thermal stability

Tungsten -nickel-iron alloy are mainly affected by tungsten, which has the highest melting point of all metals (3410°C), providing the alloy with excellent high temperature resistance. Although the melting points of nickel (melting point 1455°C) and iron (melting point 1538°C) are much lower than tungsten, in the powder metallurgy manufacturing process, tungsten particles remain solid during sintering, while nickel and iron form the matrix through liquid phase sintering, so the melting point and thermal stability of the alloy as a whole mainly depend on the characteristics of tungsten particles. The actual use temperature of tungsten- nickel-iron alloy is usually much lower than the melting point of tungsten, generally in the range of 1000-1500°C, which is sufficient to meet the needs of most high temperature applications.

Thermal stability is an important advantage of tungsten-nickel-iron alloy, which refers to its ability to maintain structure and performance in high temperature environments. Tungsten's low coefficient of thermal expansion (about $4.5 \times 10^{-6} / ^\circ \text{C}$) gives the alloy excellent dimensional stability when the temperature changes, reducing deformation or cracking caused by thermal stress. This is particularly important for applications in the aerospace field, such as turbine blade counterweights or spacecraft components, which need to maintain precise geometry under high temperature and thermal cycling conditions. The addition of nickel further enhances the thermal stability of the alloy, and its good oxidation resistance enables the alloy to resist oxidative corrosion in high temperature air environments and extend its service life.

In the military industry, the thermal stability of tungsten-nickel-iron alloy makes it an ideal material for high-temperature transient environments. For example, when the core of an armor-piercing projectile hits an armored target at high speed, it will generate instantaneous high temperatures. Tungsten-nickel-iron alloy can withstand such extreme conditions without softening or structural failure. In addition, in

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the nuclear industry, tungsten-nickel-iron alloy is used to manufacture radiation shielding containers, and its thermal stability ensures reliability in high-temperature radiation environments.

Tungsten -nickel-iron alloy is also related to its microstructure. The dense structure (density close to 99%) formed by liquid phase sintering reduces internal pores and defects, making the alloy less likely to undergo phase change or grain boundary sliding at high temperatures. Hot isostatic pressing technology further optimizes the microstructure of the alloy and improves the stability of its mechanical properties in high temperature environments. However, the ratio of nickel to iron has a certain effect on thermal stability: too high an iron content may reduce the corrosion resistance of the alloy in high temperature environments due to its lower oxidation resistance , so the formula needs to be precisely controlled.

2.2.2 Thermal expansion coefficient

Tungsten -nickel-iron alloy is an important indicator of its thermal performance, reflecting the degree of dimensional change of the material when the temperature changes. The coefficient of thermal expansion of tungsten -nickel-iron alloy is usually between $4.5\text{--}5.5 \times 10^{-6} / ^\circ\text{C}$. This low coefficient of thermal expansion is mainly due to the characteristics of tungsten (the coefficient of thermal expansion of tungsten is about $4.5 \times 10^{-6} / ^\circ\text{C}$). Nickel (about $13 \times 10^{-6} / ^\circ\text{C}$) and iron (about $12 \times 10^{-6} / ^\circ\text{C}$) have higher coefficients of thermal expansion, but because tungsten dominates the alloy (usually 85%-95%), the overall coefficient of thermal expansion of the alloy remains low, close to the characteristics of pure tungsten.

The low thermal expansion coefficient gives tungsten nickel iron alloy excellent dimensional stability in high temperature or thermal cycle environments, and can effectively resist thermal stress or deformation caused by temperature changes. This feature is particularly important in the aerospace field, such as the counterweight components used to manufacture aircraft turbine blades or the balance blocks of spacecraft, which need to maintain precise geometry under conditions of rapid heating or cooling. The low thermal expansion coefficient ensures that the alloy will not undergo significant volume expansion or contraction when the temperature fluctuates, thereby avoiding structural failure or loss of precision.

Tungsten -nickel-iron alloy is also related to its composition ratio and microstructure. For example, the thermal expansion coefficient of 90W-7Ni-3Fe alloy is about $5.0 \times 10^{-6} / ^\circ\text{C}$, while the thermal expansion coefficient of 95W-4Ni-1Fe alloy with a higher tungsten content can be close to $4.5 \times 10^{-6} / ^\circ\text{C}$, showing better dimensional stability. The ratio of nickel and iron has a certain effect on the thermal expansion coefficient: increasing the nickel or iron content will slightly increase the thermal expansion coefficient, so the density, strength and thermal expansion properties need to be weighed when designing the alloy. In addition, liquid phase sintering and hot isostatic pressing (HIP) technology in powder metallurgy process can increase the density of the alloy and reduce micro defects, thereby further enhancing its stability in thermal cycles.

In practical applications, the low thermal expansion coefficient of tungsten-nickel-iron alloy gives it significant advantages in precision instruments and high-temperature environments. For example, in

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radiation shielding equipment in the medical field, the dimensional stability of the alloy ensures the accuracy and reliability of the shield in long-term use. Similarly, in the nuclear industry, tungsten-nickel-iron alloy is used to manufacture radioactive waste containers. Its low thermal expansion coefficient can withstand the thermal stress in high-temperature radiation environments and avoid deformation or cracking of the container.

2.2.3 Thermal conductivity

Thermal conductivity of tungsten -nickel-iron alloy is another important aspect of its thermal properties, which determines the performance of the material during heat conduction. Tungsten has a high thermal conductivity of about 173 W/m·K, while nickel (about 90 W/m·K) and iron (about 80 W/m·K) have relatively low thermal conductivity. Since tungsten accounts for the dominant content in the alloy (usually 85%-95%), the thermal conductivity of tungsten -nickel-iron alloy is generally between 100-130 W/m·K, depending on the composition ratio and microstructure. This higher thermal conductivity enables the alloy to quickly transfer heat in high temperature environments, reducing the risk of local overheating.

High thermal conductivity makes tungsten-nickel-iron alloy perform well in applications that require effective heat dissipation. For example, in the aerospace field, the alloy is used to manufacture high-temperature components (such as turbine blade counterweights), and its good thermal conductivity can quickly conduct the heat generated during operation to the surrounding environment to prevent the components from failing due to overheating. In the electronics industry, tungsten-nickel-iron alloy is sometimes used as a heat sink material, using its high thermal conductivity and high density to manage the thermal load of electronic devices and ensure the stability of the equipment when operating at high power. Thermal conductivity is also closely related to the microstructure and production process of the alloy. The dense structure formed by liquid phase sintering (density close to 99%) reduces internal porosity and grain boundary scattering, thereby improving heat conduction efficiency. Hot isostatic pressing technology further optimizes the microstructure of the alloy, reduces thermal resistance, and improves thermal conductivity. However, the ratio of nickel to iron will slightly affect thermal conductivity: higher nickel or iron content may slightly reduce the overall thermal conductivity of the alloy due to its lower thermal conductivity. Therefore, in applications requiring high thermal conductivity, high tungsten content formulations such as 95W-4Ni-1Fe are usually preferred. Tungsten -nickel-iron alloy also gives it an advantage in high-temperature processing and transient thermal shock scenarios. For example, in military armor-piercing core applications, the alloy will generate instantaneous high temperatures during high-speed impacts, and its high thermal conductivity can quickly disperse the heat to prevent local softening or structural damage. In addition, the combination of thermal conductivity and low thermal expansion coefficient further enhances the performance of the alloy in thermal cycling environments, allowing it to remain stable under rapid heating and cooling conditions.

2.3 Chemical stability of tungsten-nickel-iron alloy

Tungsten -nickel-iron alloy is an important characteristic in a variety of environments, which determines

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its service life under corrosive or oxidizing conditions. The chemical stability of tungsten -nickel-iron alloy is mainly due to the excellent corrosion resistance of tungsten and nickel . Although the addition of iron slightly reduces the corrosion resistance, the alloy as a whole still shows good chemical stability by precisely controlling the ratio. This characteristic enables it to be used for a long time in humid, acidic or high temperature environments, and is widely used in marine engineering, chemical industry, medical and nuclear industries.

Tungsten has extremely high chemical stability and good corrosion resistance to most acids, alkalis and oxidants. For example, tungsten shows strong resistance to corrosion by hydrochloric acid, sulfuric acid and nitric acid at room temperature, and only reacts slightly in high-temperature concentrated nitric acid or hydrofluoric acid. This property enables tungsten-nickel-iron alloy to maintain structural integrity in acidic environments and is suitable for manufacturing corrosion-resistant parts in the chemical industry, such as counterweights for reaction vessels or pipelines.

The addition of nickel further enhances the chemical stability of the alloy. Nickel has strong corrosion resistance to moisture , salt spray and alkaline environment, especially in marine environment. The matrix formed by nickel in the alloy can form a dense oxide layer (mainly NiO) on the surface, effectively preventing further corrosion reactions. This characteristic enables tungsten-nickel-iron alloy to be used as counterweights or structural components in marine engineering, and can withstand the erosion of seawater and salt spray for a long time.

Iron has relatively weak chemical stability, and is prone to oxidative corrosion, especially in humid or acidic environments. However, in tungsten-nickel-iron alloys, the iron content is usually low (2%-5%), and the presence of nickel can make up for the deficiency of iron to a certain extent. By optimizing the ratio of nickel and iron (such as 90W-7Ni-3Fe), the corrosion resistance of the alloy can be close to the level of nickel-based alloys while maintaining high density and high strength. In addition, the dense structure formed by the liquid phase sintering process reduces the exposure of pores and grain boundaries, further reducing the possibility of corrosion.

In high temperature environments, the chemical stability of tungsten-nickel-iron alloys is due to the oxidation resistance of tungsten and nickel . Tungsten resists oxidation at high temperatures, while the nickel oxide layer protects the alloy surface from further oxidation reactions. This allows the alloy to maintain its performance in hot air or oxygen-containing environments, such as in aerospace components or nuclear industry shielding materials. It should be noted that too high an iron content may lead to increased oxidation at high temperatures, so low-iron formulations are usually selected for high-temperature applications.

Tungsten -nickel-iron alloy also makes it have important applications in the medical and nuclear industries. For example, in radiation shielding equipment, the alloy needs to be exposed to radiation and humid environments for a long time, and its excellent corrosion resistance ensures the long-term reliability and safety of the equipment. In short, the chemical stability of tungsten-nickel-iron alloy is an important guarantee for its application in many fields, combined with its high density and mechanical

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properties, making it an ideal choice for high-performance materials.

2.3.1 Corrosion resistance

Tungsten-nickel-iron alloy is one of the core characteristics of its chemical stability, which enables it to be used for a long time in a variety of corrosive environments. The corrosion resistance is mainly due to the excellent corrosion resistance of tungsten and nickel. Although the addition of iron slightly reduces this performance, the alloy as a whole still shows good corrosion resistance by precisely controlling the composition ratio. The corrosion resistance of tungsten-nickel-iron alloy makes it widely used in marine engineering, chemical industry, medical equipment and nuclear industry, especially in environments that need to resist acid, alkali or salt spray corrosion.

Tungsten has extremely high chemical stability and exhibits excellent corrosion resistance to most acids and alkalis. For example, tungsten hardly reacts to hydrochloric acid, sulfuric acid and dilute nitric acid at room temperature, and only slightly corrodes in concentrated nitric acid or hydrofluoric acid at high temperature. This property enables tungsten-nickel-iron alloys to maintain structural integrity in acidic environments, making them suitable for use in counterweights or structural components in the chemical industry, such as corrosion-resistant components of reaction vessels or pipelines. The combination of tungsten's high density and corrosion resistance enables it to provide reliable performance in a small volume.

The addition of nickel significantly enhances the corrosion resistance of the alloy. Nickel has excellent resistance to moisture, salt spray and alkaline environments, especially in marine environments. In tungsten-nickel-iron alloys, nickel (usually 5%-10%) forms a liquid phase sintering matrix, which can generate a dense oxide protective layer (mainly NiO) on the surface of the alloy, effectively preventing further erosion by corrosive media. For example, 90W-7Ni-3Fe alloy can maintain surface stability for a long time in seawater or salt spray environments, and is suitable for counterweights or structural components in marine engineering, such as ship balance blocks or marine drilling equipment.

Iron has relatively weak corrosion resistance, especially in humid or acidic environments where it is prone to oxidation. However, due to the low iron content in tungsten-nickel-iron alloys (usually 2%-5%) and the presence of nickel that can make up for the deficiency of iron, the overall corrosion resistance of the alloy is still high. The dense structure (density close to 99%) formed by the liquid phase sintering process further reduces the exposure of pores and grain boundaries, reducing the possibility of penetration of corrosive media. In addition, by optimizing the ratio of nickel to iron, a balance can be achieved between cost and performance. For example, increasing the nickel content (such as 7%-10%) can significantly improve corrosion resistance and is suitable for harsh chemical environments.

Tungsten-nickel-iron alloy is also related to its surface quality and processing technology. Polishing or coating treatment can further improve the corrosion resistance of the alloy and reduce the corrosion-inducing effect of surface defects. In practical applications, tungsten-nickel-iron alloy is often used to manufacture radiation shielding components of medical equipment, such as CT machine protective

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covers. Its corrosion resistance ensures the reliability of the equipment for long-term use in humid or sterilized environments. Similarly, in the nuclear industry, the alloy is used in the manufacture of radioactive waste containers, and its corrosion resistance ensures the safety of the containers in complex environments.

2.3.2 Antioxidant properties

Tungsten -nickel-iron alloy is an important characteristic for maintaining its performance in high temperature or oxygen-containing environments. Oxidation resistance refers to the ability of a material to resist oxidation reactions and avoid performance degradation caused by high temperature oxidation. The oxidation resistance of tungsten -nickel-iron alloy is mainly due to the chemical stability of tungsten and nickel, while the addition of iron has a certain effect on high temperature oxidation resistance. However, through reasonable formula design, the alloy can show good stability in high temperature air or other oxidizing environments.

Tungsten has excellent oxidation resistance and is almost unreactive to oxygen at room temperature to moderate temperatures (below about 800°C). Under high temperature conditions, tungsten slowly forms oxides (such as WO_3), but due to its high content (85%-95%) and dense structure in tungsten-nickel-iron alloys, the oxidation reaction is usually limited to the surface and progresses slowly. This property enables tungsten-nickel-iron alloys to maintain structural integrity in high temperature environments and is suitable for high-temperature components in the aerospace and military fields, such as turbine blade counterweights or armor-piercing projectile cores.

The oxidation resistance of nickel is the key guarantee for tungsten-nickel-iron alloy in high temperature environment. Nickel can form a stable oxide protective layer on the surface, effectively preventing oxygen from further penetrating into the alloy. This oxide layer can remain stable at high temperatures (about 600-1000°C), giving the alloy a long service life in oxygen-containing environments. For example, in the aerospace field, tungsten-nickel-iron alloy is used to manufacture high-temperature rotating parts, and its oxidation resistance ensures that the parts will not experience significant performance degradation in high-temperature air.

Iron has weak oxidation resistance, especially at high temperatures, where it easily forms iron oxide (Fe_2O_3 or Fe_3O_4), which may lead to oxidative corrosion on the alloy surface. However, due to the low iron content in the alloy (2%-5%) and the presence of nickel, which can alleviate the oxidation tendency of iron, the overall oxidation resistance of the alloy is still strong. The dense microstructure formed by liquid phase sintering further reduces the channels for oxygen penetration and enhances the oxidation resistance. In high-temperature applications, formulas with low iron content (such as 90W-7Ni-3Fe) are usually selected to optimize oxidation resistance.

Tungsten -nickel-iron alloy makes it widely used in high temperature and oxidizing environments. For example, in the nuclear industry, the alloy is used to manufacture radiation shielding containers, which can resist oxidation in high temperature radiation environments and ensure long-term reliability. In the

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medical field, the oxidation resistance of tungsten-nickel-iron alloy ensures the stability of radiation shielding equipment during high temperature sterilization or long-term exposure to air. Process optimization (such as hot isostatic pressing) can further increase the density of the alloy and reduce oxidation-sensitive micro defects, thereby enhancing the oxidation resistance.

2.3.3 Chemical reactions with other materials

Tungsten -nickel-iron alloy with other materials are an important aspect of its chemical stability, which determines its applicability in complex chemical environments. Tungsten -nickel-iron alloys generally exhibit low chemical activity and do not react significantly with most materials at room temperature. This inertness mainly stems from the high chemical stability of tungsten and nickel, which enables the alloy to coexist with a variety of materials without inducing harmful chemical reactions. However, under certain conditions (such as high temperature or highly corrosive environment), the alloy may have limited chemical reactions with certain materials, which need to be evaluated according to the application environment.

The high content of tungsten in the alloy makes it chemically inert to most common materials (e.g. water, air, salt solutions). Tungsten has very low reactivity with acids (e.g. hydrochloric acid, sulfuric acid) and may only slightly dissolve in concentrated nitric acid or hydrofluoric acid at high temperatures. When in contact with metallic materials, tungsten nickel iron alloys usually do not cause significant galvanic corrosion because the electrode potential of tungsten is high and the nickel oxide layer protects the alloy surface. For example, in mechanical parts in contact with aluminum or steel, tungsten nickel iron alloys can remain stable and are suitable for use as counterweights or connecting parts.

The chemical inertness of nickel further enhances the compatibility of the alloy with other materials. Nickel has good corrosion resistance to alkaline substances and neutral solutions (such as water or salt water), and is not easy to react chemically with common metals or non-metallic materials. In medical equipment, tungsten-nickel-iron alloys are often used together with materials such as plastics, ceramics or glass. For example, in the radiation shielding components of CT machines, the alloy has no obvious chemical reaction with the surrounding non-metallic materials and maintains long-term stability.

The presence of iron may trigger chemical reactions under certain conditions, especially in humid or acidic environments, where iron may oxidize or corrode with oxygen or chlorides. However, due to the low iron content (2%-5%) and the protective effects of nickel and tungsten, these reactions are usually limited to the surface and progress slowly. Under high temperature conditions, iron may react with oxygen or sulfides to form oxides or sulfides, so alloys with low iron formulas should be carefully selected in high temperature corrosive environments.

Tungsten -nickel-iron alloy with certain specific materials requires special attention. For example, when in contact with strong oxidants (such as concentrated nitric acid or peroxides) at high temperatures, the alloy may undergo slow surface oxidation, and surface treatment (such as coating) is required to enhance protection. In addition, tungsten may react slightly when in contact with fluorine-containing materials or

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hydrofluoric acid, so it is not recommended to use it in a strong fluorinated environment. Overall, the low chemical activity of tungsten-nickel-iron alloy enables it to coexist safely with most materials in a variety of environments, and is particularly suitable for the manufacture of multi-material composite structures.

2.4 Electromagnetic and other special properties of tungsten-nickel-iron alloy

Tungsten -nickel-iron alloy is not only known for its high density and excellent mechanical properties, but its electromagnetic properties and other special properties also give it unique advantages in specific applications. Electromagnetic properties include magnetic properties, electrical conductivity and resistivity, which are determined by the composition and microstructure of the alloy. The high density and chemical stability of tungsten provide the basis for the alloy, while the addition of nickel and iron gives it specific electromagnetic properties, making it perform well in the aerospace, electronics and military fields. The following will explore the magnetic properties, electrical conductivity and resistivity of tungsten -nickel-iron alloy in detail.

2.4.1 Magnetic properties

The magnetic properties of tungsten -nickel-iron alloy are mainly determined by the ferromagnetism of nickel and iron, while tungsten itself is a non-magnetic material (paramagnetic). Nickel and iron are both ferromagnetic elements that can be magnetized in an external magnetic field. Therefore, tungsten -nickel-iron alloy usually exhibits weak ferromagnetism, and the specific magnetic properties depend on the content and ratio of nickel and iron. Generally speaking, alloys with higher nickel content (such as 7%-10%) (such as 90W-7Ni-3Fe) have stronger magnetism, and increasing iron content (such as 3%-5%) will further enhance the magnetization intensity, but the overall magnetism is still much lower than that of pure nickel or pure iron.

Tungsten -nickel-iron alloy gives it advantages in certain specific applications. For example, in scenarios where magnetic positioning or electromagnetic shielding is required, the magnetic properties of the alloy can be utilized, such as in the aerospace field for the manufacture of electromagnetic compatible counterweights or sensor components. The magnetization intensity of the alloy (saturation magnetization is usually in the range of 0.1-0.3 T) is sufficient to meet the needs of these applications without interfering with precision electronic equipment due to excessive magnetism. In addition, the magnetism of the alloy can be optimized by heat treatment or composition adjustment, such as reducing internal stress through annealing to further improve the stability of magnetic properties.

The microstructure also has an important influence on the magnetic properties of tungsten-nickel-iron alloy. The dense structure formed by liquid phase sintering makes nickel and iron evenly distributed around the tungsten particles, forming a continuous magnetic matrix. This structure helps to improve the magnetic permeability while reducing hysteresis loss, making the alloy have better responsiveness in dynamic magnetic fields. However, too high an iron content may lead to instability in magnetic properties, especially in high temperature or corrosive environments, where iron oxidation may affect the properties

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of the magnetic matrix. Therefore, when designing alloys, the iron content is usually controlled at a lower level (such as 2%-5%) to balance magnetism and corrosion resistance.

Tungsten -nickel-iron alloy also make it have potential applications in the military field. For example, in electromagnetically driven weapon systems or magnetic sensors, the weak magnetism of the alloy can provide a moderate magnetic response, while its high density and high strength meet the structural requirements. In the medical field, the magnetic properties of tungsten-nickel-iron alloy need to be carefully considered. For example, when used near MRI equipment, it is necessary to ensure that its weak magnetism does not interfere with the uniformity of the magnetic field.

2.4.2 Conductivity

Tungsten -nickel-iron alloy is an important indicator of its electromagnetic properties, reflecting the ability of the material to conduct electric current. Electrical conductivity is usually expressed in Siemens per meter (S/m), which is the reciprocal of resistivity. The electrical conductivity of tungsten -nickel-iron alloy is affected by its composition and microstructure. Tungsten has a higher electrical conductivity (about 1.82×10^7 S/m), while nickel (about 1.43×10^7 S/m) and iron (about 1.0×10^7 S/m) have slightly lower electrical conductivity. Since tungsten dominates the alloy (85%-95%), the electrical conductivity of tungsten -nickel-iron alloy is usually between 1.0×10^7 - 1.5×10^7 S/m, which is lower than pure tungsten but higher than ordinary steel.

High electrical conductivity gives WNiFe alloys certain advantages in applications that require current conduction. For example, in the electronics industry, the alloy can be used to make electrodes or connecting components, taking advantage of its high density and electrical conductivity to ensure efficient current transfer and structural stability. In the aerospace field, WNiFe alloys are sometimes used as counterweights in electrical systems, and its electrical conductivity helps reduce resistive heat losses and improve the overall efficiency of the system. In addition, the alloy's electrical conductivity combined with its high thermal conductivity (100-130 W/m·K) makes it perform well in scenarios where it is necessary to manage both heat and current, such as heat sinks or electrical grounding components.

Electrical conductivity is also closely related to the microstructure of the alloy. The dense structure formed by liquid phase sintering and hot isostatic pressing (HIP) processes reduces the scattering effect of grain boundaries and pores and improves the efficiency of electron conduction. The ratio of nickel to iron has a certain effect on electrical conductivity: a higher nickel content helps to maintain a higher electrical conductivity, while an increase in iron content may slightly reduce the overall electrical conductivity of the alloy due to its lower electrical conductivity. Therefore, in applications that require high electrical conductivity, alloys with high tungsten and low iron formulas, such as 95W-4Ni-1Fe, are usually selected.

It should be noted that the electrical conductivity of tungsten-nickel-iron alloy may decrease slightly at high temperatures, because the increase in temperature increases electron scattering and reduces the conductivity efficiency. However, due to the high melting point and thermal stability of tungsten, the

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conductivity of the alloy changes relatively little in high temperature environments, making it suitable for use in high-temperature electronic devices. Overall, the electrical conductivity of tungsten-nickel-iron alloy makes it practical in electrical and electronic applications, especially in scenarios where high density and conductive properties are required.

2.4.3 Resistivity

Electrical Resistivity is the reciprocal of conductivity, reflecting the ability of a material to block the passage of electric current, and is usually expressed in ohm-meter ($\Omega \cdot m$). The resistivity of tungsten - nickel-iron alloy is generally between $6.7 \times 10^{-8} - 1.0 \times 10^{-7} \Omega \cdot m$, the specific value depends on the composition ratio and microstructure. Tungsten has a low resistivity (about $5.5 \times 10^{-8} \Omega \cdot m$), while nickel (about $7.0 \times 10^{-8} \Omega \cdot m$) and iron (about 1.0×10^{-7}). Since tungsten is the main component of the alloy, the resistivity of the alloy is close to that of tungsten, but slightly higher than that of pure tungsten.

The lower resistivity gives tungsten-nickel-iron alloy an advantage in applications that require efficient current conduction. For example, in electronic devices, the alloy can be used as a conductive component or electrode material, using its low resistivity to reduce energy loss while its high density meets structural requirements. In the military field, the low resistivity of tungsten-nickel-iron alloy makes it potentially applicable in electromagnetic drive systems (such as electromagnetic guns), which can efficiently conduct large currents while withstanding high stress and instantaneous high temperatures.

Resistivity is closely related to the microstructure of the alloy. Liquid phase sintering and hot isostatic pressing in powder metallurgy processes can form a high-density structure, reduce the obstacles to electron conduction caused by grain boundaries and defects, and thus reduce resistivity. The ratio of nickel to iron has a certain effect on resistivity: a higher iron content will slightly increase the resistivity, while the addition of nickel helps to keep the resistivity low. For example, the resistivity of 90W-7Ni-3Fe alloy is about $8.0 \times 10^{-8} \Omega \cdot m$, while the resistivity of 95W-4Ni-1Fe alloy can be as low as $7.0 \times 10^{-8} \Omega \cdot m$.

In high temperature environments, the resistivity of tungsten nickel iron alloy increases slightly with increasing temperature due to enhanced electron scattering. However, the high melting point and thermal stability of tungsten ensure that the resistivity changes little, allowing the alloy to maintain good conductivity in high temperature electronic applications. In addition, the resistivity of the alloy combined with its corrosion resistance allows it to maintain stable electrical properties in humid or chemical environments, making it suitable for use in conductive parts in marine engineering or the chemical industry.

2.4.4 Radiation resistance

Tungsten -nickel-iron alloy is one of its important characteristics in the nuclear industry and medical field, making it a preferred choice for radiation shielding materials. The radiation resistance mainly comes from the high atomic number ($Z=74$) and high density of tungsten (the alloy density is usually

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between 16.5-18.75 g/cm³), which gives the alloy a strong ability to absorb and shield high-energy radiation such as X-rays, gamma rays and neutron radiation. Although nickel and iron, as binding phases, contribute less to radiation shielding, their radiation resistance can be further enhanced by optimizing the alloy's microstructure and composition ratio.

The high atomic number of tungsten gives it a high photoelectric effect and Compton scattering probability when interacting with high-energy photons (such as X-rays and gamma rays), thereby effectively attenuating the radiation energy. Compared with traditional shielding materials such as lead (density 11.34 g/cm³, Z=82), tungsten -nickel-iron alloy has higher density and mechanical strength, and can achieve the same shielding effect at a thinner thickness while avoiding the toxicity and environmental problems of lead. For example, in the medical field, tungsten-nickel-iron alloy is widely used to manufacture protective covers for CT machines and X-ray equipment. Its high density allows the design of more compact equipment and reduces space occupancy.

In the nuclear industry, the radiation resistance of tungsten-nickel-iron alloy makes it suitable for radioactive waste containers and nuclear reactor shielding components. The alloy can not only effectively shield gamma rays, but also has a certain absorption capacity for neutron radiation. Neutron shielding usually requires the combination of other materials (such as boron compounds), but the high density and structural stability of tungsten-nickel-iron alloy make it an ideal substrate in composite shielding systems. In addition, the corrosion resistance and thermal stability of the alloy ensure its reliability for long-term use in radiation environments, such as no performance degradation under high temperature or humidity conditions.

Tungsten -nickel-iron alloy is also closely related to its microstructure. Liquid phase sintering and hot isostatic pressing (HIP) technology in powder metallurgy process enables the alloy to reach a density close to the theoretical value (more than 99%), reducing porosity and defects, thereby reducing the possibility of radiation penetration. The ratio of nickel to iron has little effect on shielding performance, but high tungsten content (such as 95W-4Ni-1Fe) usually has better radiation resistance because the tungsten content directly determines the density and radiation absorption capacity of the alloy.

It should be noted that the long-term stability of tungsten-nickel-iron alloy in a strong radiation environment may be affected by nickel and iron. Nickel and iron may undergo slight changes in crystal structure under high-dose radiation, resulting in slight performance changes. Therefore, in extreme radiation environments, it is necessary to further improve radiation resistance through surface coating or optimized formulation (such as reducing iron content). Overall, the radiation resistance of tungsten-nickel-iron alloy gives it significant advantages in applications in the medical, nuclear and aerospace fields (such as satellite radiation protection).

2.5 CTIA GROUP LTD Tungsten Nickel Iron Alloy MSDS

Chemicals and company logos : This material is Tungsten Nickel Iron Alloy, produced by CTIA GROUP LTD. **Composition/Composition Information :** Tungsten -nickel-iron alloy is a high-density

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alloy, mainly composed of the following components: tungsten (W, CAS No.: 7440-33-7, 85%-95%), nickel (Ni, CAS No.: 7440-02-0, 5%-10%), iron (Fe, CAS No.: 7439-89-6, 2%-5%). The alloy is made by powder metallurgy process, with tungsten as the main component, nickel and iron as the bonding phase, trace impurities may exist but will not affect the main performance. **Hazard Overview** : Tungsten -nickel-iron alloy is relatively safe in bulk form.

1. Physical and chemical properties

Tungsten -nickel-iron alloy is a silver-grey metallic solid with a density of 16.5-18.75 g/cm³. Affected by the nickel-iron matrix, its melting point is about 1450-1500°C. It is insoluble in water and resistant to most acid and alkali corrosion. It is stable in block form.

2. Stability and reactivity

The alloy is chemically stable at room temperature, but should avoid contact with strong oxidants (such as nitric acid, peroxide) or hydrofluoric acid at high temperatures. Prohibited materials include strong oxidants and sulfur to prevent potential chemical reactions.

3. Toxicology information

Nickel compounds are classified as Class 1 carcinogens by IARC. Long-term inhalation of nickel dust may cause respiratory diseases or allergic reactions. Tungsten and iron are less toxic, but inhalation of dust may cause mechanical irritation. Long-term exposure to dust should be avoided.

4. Ecological information

Tungsten -nickel-iron alloy is insoluble in water and has a low impact on the environment. However, waste must be handled in accordance with environmental regulations to ensure ecological safety.

5. Shipping Information

Tungsten -nickel-iron alloy is not a dangerous cargo and can be transported as general metal material.

6. Regulatory Information

This MSDS complies with GB/T 16483-2008 Contents and Item Sequence of Chemical Safety Data Sheets. Nickel

7. Other Information

This MSDS is based on a typical tungsten -nickel-iron alloy formula. The specific data may vary slightly due to different formulas.

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CTIA GROUP LTD
Tungsten Nickel Iron Alloy Introduction

1. Overview of Tungsten Nickel Iron Alloy

Tungsten-nickel-iron alloy is a high-density material with tungsten as the primary component and nickel and iron added as binder phases. Known for its excellent physical and chemical properties, it is widely used in aerospace, military, medical, nuclear industries, and civilian fields. CTIA GROUP LTD offers tungsten-nickel-iron alloy products, including alloy rods, counterweights, radiation shields, and phone vibrators, tailored for various applications.

2. Features of Tungsten Nickel Iron Alloy

High Density: Typically ranges from 16.5 to 18.75 g/cm³.

High Strength: Tensile strength ranges from 700 to 1000 MPa.

Other Characteristics: Exhibits strong radiation absorption, high thermal conductivity, low thermal expansion coefficient, good electrical conductivity, plasticity, weldability, and processability.

3. Tungsten-Nickel-Iron Alloy Grades

Grade	Class 1	Class 1	Class 2	Class 2	Class 3	Class 3	Class 4
Composition (%)	90W 7Ni3Fe	91W 6Ni3Fe	92W 5Ni3Fe	93W 4Ni3Fe	95W 3Ni2Fe	96W 3Ni1Fe	97W 2Ni1Fe
Density (g/cm ³)	17.1	17.25	17.50	17.60	18.10	18.30	18.50
Heat Treatment	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering
Tensile Strength (PSI)	900~1000		900~1100		920~1100		
Elongation (%)	18~29	17~27	16~26	16~24	10~22	8~20	6~13
Hardness (HRC)	24~28	25~29	25~29	26~30	27~32	28~34	28~36

4. Production Methods for Tungsten Nickel Iron Alloy

The powder metallurgy process involves first mixing tungsten powder, nickel powder, and iron powder; then ball milling and sieving; followed by shaping the mixed powder into blanks using hot pressing, hot isostatic pressing, or vacuum sintering techniques; and finally improving the alloy's microstructure and properties through heat treatments such as annealing or quenching.

5. Applications of Tungsten Nickel Iron Alloy

In the medical field, tungsten-nickel-iron alloy serves as radiation shields, radiation source containers, collimators, isotope containers, and syringe shields. In scientific research, tungsten alloy is used as heat sinks and for oil drilling and mineral resource exploration.

6. Purchasing Information

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Chapter 3 Preparation and Processing of Tungsten-Nickel-Iron Alloy

3.1 Raw material selection and pretreatment

Tungsten-nickel-iron alloy has a crucial influence on its final performance, and the raw material selection and pretreatment are the starting point of the entire process, which directly determines the purity, microstructure and performance stability of the alloy. Tungsten-nickel-iron alloy is mainly produced by powder metallurgy process, which involves the selection and pretreatment of three main raw materials: tungsten, nickel and iron. The purity, particle size and chemical properties of the raw materials will significantly affect the sintering effect, the density and mechanical properties of the alloy. Therefore, scientific and reasonable raw material selection and pretreatment process are the key links to ensure the quality of the alloy. The following will discuss in detail the purity requirements of tungsten, nickel and iron and the pretreatment process of raw materials.

3.1.1 Purity requirements for tungsten, nickel and iron

Tungsten-nickel-iron alloy is highly dependent on the purity of the raw materials, as impurities may cause microstructural defects, performance degradation or increased processing difficulty. Tungsten, nickel and iron are the main components of the alloy, and their purity requirements are usually determined by the application scenario (such as aerospace, military or medical) and performance requirements. The following are the purity requirements of each element and their impact on the performance of the alloy.

Tungsten (W) : Tungsten is the main component of tungsten-nickel-iron alloy, accounting for 85%-95%. Its purity is crucial to the density, hardness and radiation resistance of the alloy. The industry usually requires the purity of tungsten powder to reach 99.9% (3N) or higher, preferably above 99.95% (4N) to reduce the influence of impurities such as oxygen, carbon, and sulfur. Excessive oxygen content ($>0.05\%$) may lead to the formation of oxide inclusions during sintering, reducing the density and mechanical properties of the alloy; carbon or sulfur impurities may cause grain boundary embrittlement and affect toughness. In high-precision applications, high-purity tungsten powder (99.99%) is required to ensure excellent radiation resistance and chemical stability.

Nickel (Ni) : Nickel acts as a bonding phase, accounting for 5%-10%, and is responsible for improving the toughness and corrosion resistance of the alloy. The purity of nickel is usually required to reach 99.8% (2N8) or above, preferably 99.9% (3N). Common impurities in nickel include sulfur, phosphorus and silicon. Excessive sulfur content ($>0.01\%$) may lead to the formation of a low melting point phase during sintering, affecting the thermal stability of the alloy; phosphorus may reduce toughness, and silicon may affect the uniformity of liquid phase sintering. High-purity nickel can ensure the formation of a stable matrix during liquid phase sintering, enhance the bonding force of tungsten particles, and thus improve the tensile strength (800-1000 MPa) and elongation (10%-20%) of the alloy.

Iron (Fe) : Iron accounts for 2%-5% of the alloy and is used to enhance hardness and reduce costs. Its purity requirement is usually 99.5% (2N5) or above. The main impurities in iron are oxygen, carbon and

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nitrogen. Too high oxygen content ($>0.1\%$) may cause iron oxide to form during sintering, reducing corrosion resistance; too high carbon content ($>0.05\%$) may cause carbide precipitation and affect the toughness of the alloy. In some high corrosion resistance applications (such as marine engineering), higher purity iron (99.9%) is required to reduce corrosion tendency. The purity of iron also affects the magnetic properties of the alloy. A lower impurity content helps maintain stable weak ferromagnetism.

In order to meet the needs of different applications, the selection of raw material purity needs to be optimized according to the specific formula and performance requirements. For example, 90W-7Ni-3Fe alloy requires high density and high strength in the military field (such as armor-piercing core), so high-purity tungsten (99.95%) and nickel (99.9%) are preferred; while in the civilian field (such as sports equipment weights), the purity of iron can be appropriately reduced to control costs. Suppliers usually provide raw materials that meet ASTM B777 or ISO standards to ensure purity and consistency.

3.1.2 Raw material pretreatment process

Raw material pretreatment is an important step in the preparation of tungsten-nickel-iron alloy, which aims to optimize the particle size, morphology and chemical state of tungsten, nickel and iron powders to ensure the smooth progress of subsequent mixing, pressing and sintering processes. The pretreatment process includes powder screening, cleaning, reduction and activation, and each step has an important influence on the final performance of the alloy.

Powder screening : Tungsten, nickel, and iron powders need to be screened to remove oversized or undersized particles to ensure uniform particle size distribution. The particle size of tungsten powder is usually controlled at 1-10 microns, preferably 3-5 microns, to ensure high density and uniform microstructure during sintering. The particle size of nickel and iron powders is slightly larger, usually 5-20 microns, to promote fluidity during liquid phase sintering. Screening usually uses a vibrating screen or airflow classification equipment, and the screen size is selected according to the target particle size (for example, 200-400 mesh). Uniform particle size distribution helps to improve mixing uniformity and sintering efficiency and reduce porosity.

Cleaning and impurity removal : The raw powder may contain surface oxides, oil or other impurities that need to be removed by cleaning. Tungsten powder is usually cleaned in a dilute acid (such as dilute hydrochloric acid) to remove surface oxides (WO_3), then rinsed with deionized water and dried. Nickel and iron powders should be cleaned carefully to avoid introducing new oxides. They are usually cleaned with organic solvents (such as ethanol) and then dried in a vacuum or inert gas (such as nitrogen) environment. The cleaning process needs to control time and temperature to avoid powder agglomeration or changes in chemical properties.

Reduction treatment : Tungsten powder may contain oxides (such as WO_2 or WO_3) during the production process, which need to be removed by hydrogen reduction treatment. Reduction is usually carried out in a hydrogen atmosphere furnace at $700-900^{\circ}C$ for 1-2 hours to ensure that the oxygen content drops below 0.05% . Nickel and iron powders may also require mild reduction treatment to

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remove the surface oxide layer and improve the sintering activity of the powder. The reduction process requires strict control of atmosphere purity (hydrogen purity >99.99%) to avoid introducing new impurities.

Powder activation : To improve the sintering activity of the powder, the tungsten powder can be mechanically activated, such as high-energy ball milling. Ball milling can refine the tungsten particles (to 1-3 microns), increase its surface energy, and promote the combination with nickel and iron. The ball milling time is usually controlled at 2-4 hours. Too long may introduce impurities or cause particle agglomeration. Nickel and iron powders generally do not need too much activation because their lower melting points are sufficient to form a liquid phase during sintering. The activation process needs to be carried out in an inert atmosphere (such as argon) to prevent oxidation.

Mixing pretreatment : In some cases, tungsten, nickel, and iron powders need to be premixed or additives added before formal mixing to improve powder fluidity. For example, a small amount of organic binder (such as polyvinyl alcohol, PVA, 0.1%-0.5%) can be added to enhance the pressing performance of the powder. Premixing usually uses a V-type mixer or a three-dimensional mixer for 4-8 hours to ensure that the components are evenly distributed. Avoid introducing moisture or air during the mixing process to prevent oxidation.

Powder with too large a particle size may lead to incomplete sintering and reduce density; too high an oxygen content may cause pores or inclusions, affecting mechanical properties. Therefore, the pretreatment process parameters must be strictly controlled, and the chemical composition of the raw materials must be analyzed by X-ray fluorescence spectroscopy (XRF) or inductively coupled plasma spectroscopy (ICP) to ensure that the purity and quality requirements are met. These steps lay a solid foundation for the high-performance preparation of tungsten-nickel-iron alloys.

3.2 Preparation method of tungsten-nickel-iron alloy

Tungsten -nickel-iron alloy mainly relies on powder metallurgy technology, which is a method of forming dense materials by mixing, pressing and sintering metal powders. The powder metallurgy process can effectively overcome the processing difficulties caused by the high melting point (3410°C) and brittleness of pure tungsten materials , and at the same time, through the bonding effect of nickel and iron, it gives the alloy excellent mechanical properties and machinability. The preparation process of tungsten -nickel-iron alloy usually includes steps such as raw material mixing, pressing, sintering and post-processing, among which liquid phase sintering technology is the key to achieving high density and high performance. The following will discuss in detail the powder metallurgy method and its core technology-liquid phase sintering technology.

3.2.1 Powder Metallurgy

Powder metallurgy is the main industrial method for preparing tungsten -nickel-iron alloys, which is suitable for producing high-density (16.5-18.75 g/cm³) and high-strength (tensile strength 800-1000 MPa)

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alloy parts. This method forms a dense alloy structure by mixing high-purity tungsten, nickel and iron powders in a specific proportion, pressing and sintering at high temperature. Its advantages are that it can accurately control the proportion of components, achieve complex geometric shapes, and is suitable for large-scale production. The following are the main steps and key technical points of preparing tungsten-nickel-iron alloys by powder metallurgy.

Raw material mixing : The preparation process begins with mixing high-purity tungsten powder (purity $\geq 99.9\%$, particle size 1-10 microns), nickel powder (purity $\geq 99.8\%$, particle size 5-20 microns) and iron powder (purity $\geq 99.5\%$, particle size 5-20 microns) in a target ratio (such as 90W-7Ni-3Fe). Mixing is usually carried out in a V-type mixer or a three-dimensional mixer for 4-8 hours to ensure that the components are evenly distributed. The mixing process must be carried out under the protection of an inert gas (such as argon or nitrogen) to prevent oxidation of the powder. To improve the fluidity of the powder, a small amount of organic binder (such as polyvinyl alcohol, 0.1%-0.5%) can be added, but it must be ensured that it is completely volatilized during subsequent sintering.

Compression molding : The mixed powder is pressed into a green body by cold isostatic pressing (CIP) or compression molding. Cold isostatic pressing is usually carried out at a pressure of 100-200 MPa, which can form a uniform green body and is suitable for the production of complex-shaped parts. Compression molding is suitable for simple shapes, and the pressure is generally 50-150 MPa. During the pressing process, the pressure and holding time (usually 1-3 minutes) need to be controlled to ensure that the green body has sufficient strength (green strength) for subsequent handling. The density of the green body is usually 50%-70% of the theoretical density, which provides a basis for subsequent sintering.

Sintering : The pressed green body is sintered at high temperature to form a dense alloy structure. Sintering is usually carried out in a vacuum or hydrogen atmosphere furnace, and the temperature is controlled at 1400-1550°C, which is lower than the melting point of tungsten but higher than the melting points of nickel (1455°C) and iron (1538°C), so that nickel and iron form a liquid phase and promote the bonding of tungsten particles. The sintering time is 1-4 hours, depending on the green body size and target density. After sintering, the density of the alloy can reach more than 99% of the theoretical value, significantly improving the mechanical properties.

Post-processing : Sintered alloys may require further processing such as heat treatment, machining or surface treatment. Heat treatment (such as annealing) can eliminate internal stresses and improve toughness. Machining (such as turning, milling or EDM) is used to form the final shape, and carbide tools are required to cope with the high hardness of the alloy (Vickers hardness 250-400). Surface treatment (such as polishing or coating) can enhance corrosion resistance or wear resistance.

The advantage of powder metallurgy is its flexibility and efficiency, which can produce a variety of products from small precision parts to large counterweights. However, process parameters (such as mixing uniformity, pressing pressure and sintering temperature) need to be strictly controlled to avoid problems such as porosity, inclusions or component segregation. Powder metallurgy can also be combined with other technologies (such as hot isostatic pressing) to further optimize performance,

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making tungsten-nickel-iron alloys widely used in aerospace, military and medical fields.

3.2.2 Liquid Phase Sintering Technology

Tungsten-nickel-iron alloy by powder metallurgy, which is responsible for forming a high-density and high-performance alloy structure. Compared with solid phase sintering, liquid phase sintering utilizes the liquid properties of nickel and iron at high temperatures to significantly improve the bonding efficiency of tungsten particles and the density of the alloy. The key to liquid phase sintering is to control the sintering temperature, atmosphere and time to ensure the formation and uniform distribution of the liquid phase, while avoiding overburning or liquid phase loss.

Liquid phase sintering principle : During the sintering process, the temperature rises to 1400-1550°C, which exceeds the melting point of nickel and iron but is much lower than the melting point of tungsten. Nickel and iron melt to form a liquid phase, filling the gaps between tungsten particles and promoting the rearrangement and bonding of tungsten particles through capillary action. The presence of the liquid phase reduces the temperature and time required for sintering, while increasing the density (nearly 99%). The tungsten particles remain solid and are embedded in the nickel-iron matrix to form a uniform composite structure, giving the alloy high strength (800-1000 MPa) and appropriate toughness (elongation 10%-20%).

Process conditions : Liquid phase sintering is usually carried out in a vacuum or hydrogen atmosphere furnace to prevent oxidation. Hydrogen atmosphere (purity>99.99%) can effectively remove trace oxides in the powder and improve the sintering quality. The sintering temperature needs to be precisely controlled above the nickel-iron liquid phase formation point (about 1450°C) but below the temperature of excessive liquid phase evaporation (about 1600°C). The holding time is generally 1-3 hours. Too long may cause liquid phase loss or grain growth, reducing performance. The cooling rate also needs to be controlled (usually 10-20°C/min) to avoid microcracks caused by thermal stress.

Microstructure influence : The microstructure formed by liquid phase sintering consists of tungsten particles (size 10-50 microns) and a nickel-iron matrix. The tungsten particles are nearly spherical or polygonal and are evenly distributed in the matrix, ensuring high density and uniform mechanical properties. Liquid phase sintering can significantly reduce porosity (<1%) and improve tensile strength and wear resistance. The ratio of nickel to iron has an important influence on the microstructure: a higher nickel content (such as 7%) increases the toughness of the matrix, while an increased iron content (such as 3%) increases the hardness.

Technical optimization : To further improve the liquid phase sintering effect, hot isostatic pressing (HIP) can be used as an auxiliary process. After sintering, hot isostatic pressing treats the green body with an isotropic pressure of 100-200 MPa and a temperature of 1200-1400°C, which can eliminate residual pores and increase the density to more than 99.5%. In addition, the addition of trace elements (such as cobalt or copper) can optimize the wettability of the liquid phase and improve the bonding of tungsten particles to the matrix. The sealing of the sintering furnace and the purity of the atmosphere are crucial

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to the process stability and need to be checked regularly to avoid oxygen or moisture contamination.

The advantages of liquid phase sintering technology are its high efficiency and high density, which enable tungsten-nickel-iron alloys to meet the high performance requirements of aerospace counterweights, military armor-piercing cores, and medical radiation shielding. However, liquid phase sintering has high requirements for equipment (such as high-precision temperature control furnaces), and process parameters need to be precisely optimized to avoid excessive or insufficient liquid phase. The successful application of liquid phase sintering technology is the key to achieving excellent performance of tungsten-nickel-iron alloys, and has promoted its widespread application in the field of high technology.

3.2.3 Additive Manufacturing (3D Printing) Technology

Additive Manufacturing (AM) or 3D printing technology is a method of directly manufacturing complex-shaped parts by stacking materials layer by layer, and it has gradually attracted attention in the preparation of tungsten-nickel-iron alloys. This technology can achieve high design freedom, reduce material waste, and is suitable for rapid prototyping of parts with complex geometries. Tungsten-nickel-iron alloys have high requirements for 3D printing processes due to their high density ($16.5-18.75 \text{ g/cm}^3$) and high melting point (tungsten melting point 3410°C), but by optimizing process parameters, it has shown significant potential in the aerospace, medical and military fields.

3D printing of tungsten-nickel-iron alloy mainly uses selective laser melting (SLM) or electron beam melting (EBM) technology. SLM uses a high-power laser beam to melt metal powder layer by layer, while EBM uses an electron beam to melt powder in a vacuum environment. Both methods deposit and melt tungsten, nickel, and iron mixed powder (or pre-alloyed powder) layer by layer to form dense alloy parts. The lower melting points of nickel and iron (1455°C and 1538°C) help form a liquid phase and promote the bonding of tungsten particles, similar to the mechanism of liquid phase sintering.

Powder preparation is a key step in 3D printing. High-purity tungsten powder (purity $\geq 99.9\%$, particle size 10-50 microns), nickel powder (purity $\geq 99.8\%$) and iron powder (purity $\geq 99.5\%$) are required, mixed in a target ratio (such as 90W-7Ni-3Fe), or pre-alloyed powder is used to ensure composition consistency. The powder needs to have good fluidity (usually through spheroidization) and uniform particle size distribution to ensure stability during printing.

Printing process parameters need to be precisely optimized to ensure quality. In SLM, the laser power is usually 200-400 W, the scanning speed is 500-1500 mm/s, and the layer thickness is 20-50 microns; EBM needs to be operated in a vacuum environment with an electron beam power of 3-6 kW. Optimizing the energy density can avoid cracks or pores and ensure that the density reaches more than 98%. After printing, the parts usually need to be heat treated (such as annealing, $800-1000^\circ\text{C}$) to eliminate residual stress, and may be combined with hot isostatic pressing (HIP, $1200-1400^\circ\text{C}$, 100-200 MPa) to further increase the density to 99.5%.

The advantage of 3D printing is that it can directly manufacture complex-shaped tungsten-nickel-iron

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alloy parts, such as aerospace counterweights or medical radiation shielding parts, reducing traditional processing steps. However, the high melting point and thermal conductivity of tungsten ($173 \text{ W/m}\cdot\text{K}$) lead to large thermal gradients and easy cracking; the powder cost is high, and the printing equipment needs to be controlled with high precision. Nickel and iron may volatilize when melted at high temperatures, and the composition needs to be controlled by argon protection or pre-alloyed powder. Currently, SLM technology can achieve a tensile strength of 700-900 MPa, which is close to traditional powder metallurgy products.

3D printed tungsten-nickel-iron alloys can be used to manufacture turbine blade balance blocks in the aerospace field, customized radiation shielding components in the medical field, and high-precision armor-piercing projectile cores in the military field. With the advancement of printing equipment and powder preparation technology, 3D printing is expected to become an important technology for the preparation of tungsten-nickel-iron alloys, especially in the production of small batches and complex-shaped parts.

3.2.4 Other preparation techniques

In addition to powder metallurgy and additive manufacturing, the preparation of tungsten-nickel-iron alloys also includes technologies such as mechanical alloying, plasma spraying and metal injection molding. These methods provide unique advantages for specific application scenarios (such as complex shapes, wear-resistant coatings or high-performance components), supplementing the limitations of traditional processes.

Mechanical alloying (MA) is a method of preparing composite powders by high-energy ball milling. High-energy ball milling causes tungsten, nickel, and iron powders to undergo plastic deformation, fracture, and cold welding to form a uniform composite powder and improve sintering activity. The process uses a planetary ball mill with a ball-to-material ratio of 10:1 to 20:1 and a ball milling time of 10-20 hours. It must be carried out under argon protection to prevent oxidation. The resulting powder is formed into a dense alloy by cold isostatic pressing and sintering. This method can refine tungsten particles (to 1-3 microns), improve alloy uniformity and mechanical properties, and is suitable for the production of high-strength components such as military armor-piercing projectile cores, but the process time is long and impurities are easily introduced.

Plasma spraying sprays tungsten, nickel, and iron powders onto the substrate surface through a high-temperature plasma flame to form a high-density coating or near-net-shape component. The powder particle size is 20-50 microns, and the spraying is carried out under the protection of argon or helium. After spraying, the performance can be optimized by heat treatment or machining. This method is suitable for the preparation of wear-resistant or corrosion-resistant coatings for industrial molds or aerospace high-temperature resistant parts, but the coating density is low (about 95%) and is not suitable for large-volume parts.

Metal Injection Molding (MIM) mixes tungsten, nickel, and iron powders with organic binders (such as

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polypropylene or wax, 10%-20%) to form an injectable slurry, and prepares complex-shaped blanks through an injection molding machine. Debinding is performed at 400-600°C, and sintering is completed in a hydrogen or vacuum atmosphere at 1400-1500°C. MIM is suitable for the production of small, complex-shaped parts, such as precision shielding parts in medical equipment or counterweights for electronic devices, but the binder removal process is complicated and trace amounts of carbon may remain, affecting performance.

These technologies are selected according to application requirements and production scale. Mechanical alloying is suitable for high-performance small-batch production, plasma spraying is suitable for surface strengthening, and MIM is good at mass production of complex-shaped parts. In the future, process optimization and equipment upgrades (such as more efficient plasma spraying or low-cost MIM) will further enhance the application prospects of these technologies and meet the diverse needs of tungsten - nickel-iron alloys in the field of high technology.

3.3 Processing technology of tungsten-nickel-iron alloy

Tungsten -nickel-iron alloy is the key link to ensure that its final parts meet the design requirements and performance needs. Due to its high density (16.5-18.75 g/cm³), high hardness (Vickers hardness 250-400) and excellent mechanical properties, the processing process requires special equipment and processes to overcome its high hardness and moderate toughness. Common processing technologies include machining and heat treatment technologies, which can accurately shape, optimize performance and improve the surface quality and environmental adaptability of the alloy. The following will discuss in detail the application of machining and heat treatment technologies in the processing of tungsten-nickel-iron alloy and its key technical points.

3.3.1 Machining

Machining is an important step in the preparation of final parts of tungsten-nickel-iron alloys. It is used to process the sintered green body into precise geometric shapes to meet the high-precision requirements of aerospace, military and medical fields. The high hardness and moderate toughness of tungsten -nickel-iron alloys make it difficult to process, but by selecting appropriate tools, processing parameters and process methods, high-efficiency and high-precision processing can be achieved.

Processing characteristics : The high hardness (HV 250-400) and high density of tungsten -nickel-iron alloy cause greater wear on the tool during processing, while its moderate toughness (elongation 10%-20%) requires controlled cutting force during processing to avoid surface cracks or deformation. Common machining methods include turning, milling, drilling, grinding and electrical discharge machining (EDM), and each method needs to be selected according to the shape and precision requirements of the component.

Turning and milling : Turning and milling are used to process regular shaped parts, such as cylindrical counterweights or armor-piercing projectile cores. Carbide tools (such as WC-Co) or cubic boron nitride

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(CBN) tools are required because of their wear resistance and can cope with the high hardness of the alloy. The cutting speed is usually controlled at 20-50 m/min, the feed rate is 0.05-0.2 mm/r, and the cutting depth is 0.1-1 mm. Coolant (such as water-based cutting fluid) is required during processing to reduce cutting temperature, tool wear and thermal damage to the workpiece surface. High-speed CNC machine tools can improve processing accuracy.

Drilling : Drilling is used to make holes or threaded structures, such as mounting holes in aerospace counterweights. Carbide drills are required, and the drilling speed is controlled at 10-30 m/min and the feed rate is 0.02-0.1 mm/r. Deep hole drilling requires step-by-step drilling and sufficient cooling to avoid drill breakage or rough hole walls. After processing, the hole diameter accuracy needs to be checked to meet the design requirements.

Grinding : Grinding is used for high-precision surface processing, such as surface flattening of medical radiation shielding components. Diamond or CBN grinding wheels are preferred because of their high hardness and can effectively grind alloys. The grinding speed is 20-30 m/s, the feed rate is 0.01-0.05 mm/time, and coolant is required to control the grinding temperature.

Electrospark machining (EDM) : For complex shapes or high-precision parts, such as tiny shielding parts for medical devices, electrospark machining is an effective method. EDM uses electric spark discharge to remove material and is suitable for machining complex geometries that are difficult to cut. Copper or graphite electrodes are used during machining, the working fluid is insulating oil, and the current is controlled at 5-20 A. EDM can achieve high precision (tolerance ± 0.005 mm), but the processing speed is slow and it is suitable for small batch production.

Processing considerations : Machining requires strict control of tool wear and workpiece surface quality to avoid microcracks or surface stress concentration. Ultrasonic cleaning is usually performed after machining to remove cutting fluid residues, and polishing may be used to further improve the surface finish. To improve corrosion resistance, a surface coating (such as Ni-P plating) can be applied. The successful implementation of machining requires high-precision equipment and skilled operation to ensure the dimensional accuracy and performance stability of tungsten -nickel-iron alloy parts.

3.3.2 Heat treatment technology

Heat treatment technology is an important part of WNiFe alloy processing, which is used to optimize its microstructure, eliminate internal stress, and improve mechanical properties and environmental adaptability. The heat treatment of WNiFe alloy usually includes annealing, aging treatment and solution treatment. The specific process selection depends on the alloy composition and application requirements. Heat treatment can improve the toughness, tensile strength (800-1000 MPa) and fatigue resistance of the alloy while maintaining its high density and high hardness characteristics.

Annealing : Annealing is the most commonly used heat treatment method for tungsten-nickel-iron alloys, which is used to eliminate residual stress generated during sintering or machining, and improve

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toughness and machinability. Annealing is usually carried out in a vacuum or hydrogen atmosphere furnace, with the temperature controlled at 800-1000°C, the holding time is 1-2 hours, and the cooling rate is controlled at 5-10°C/min to avoid thermal stress. After annealing, the elongation of the alloy can be increased to 15%-25%, and the tensile strength decreases slightly but still remains at 700-900 MPa, which is suitable for applications requiring high toughness, such as aerospace counterweights.

Aging treatment : Aging treatment is used to further optimize the strength and hardness of the alloy, especially in high tungsten content alloys (such as 95W-4Ni-1Fe). Aging treatment is carried out at 500-700°C for 2-4 hours, usually under vacuum or inert gas protection (such as argon). During the aging process, microscopic precipitation phases (such as Ni-Fe compounds) in the nickel-iron matrix enhance the matrix strength and increase the Vickers hardness of the alloy to 350-400 HV. This treatment is suitable for applications such as military armor-piercing cores that require high hardness, but may slightly reduce toughness.

Solution treatment : Solution treatment is suitable for adjusting the microstructure of the alloy and enhancing the uniformity of the nickel-iron matrix. The treatment temperature is 1100-1200°C, kept at this temperature for 1-2 hours, followed by rapid cooling (usually water quenching or gas quenching). Solution treatment can dissolve uneven precipitates and improve the chemical uniformity of the matrix, thereby improving corrosion resistance and fatigue resistance. Solution treatment is usually combined with low-temperature aging (500-600°C) to restore strength. Solution treatment is suitable for alloy parts in the marine engineering or medical fields that require high corrosion resistance .

Heat treatment equipment and process control : Heat treatment requires the use of a high-precision vacuum furnace or a hydrogen atmosphere furnace to ensure the purity of the atmosphere (>99.99%) to prevent oxidation. The temperature control accuracy must reach $\pm 5^{\circ}\text{C}$, and the cooling process must be uniform to avoid microcracks caused by thermal stress. After heat treatment, the microstructure needs to be analyzed by metallographic microscopy or X-ray diffraction (XRD) to ensure the uniformity of the tungsten particles and the nickel-iron matrix. Mechanical property tests (such as tensile tests or hardness tests) are used to verify the heat treatment effect.

Application and optimization : The selection of heat treatment process and parameter optimization should be based on specific application requirements. For example, aerospace counterweights are preferred to be annealed to improve toughness, while military armor-piercing projectile cores tend to be aged to enhance hardness. Heat treatment can also be combined with mechanical processing, such as annealing first to improve machinability, and then finishing and aging treatment to optimize performance. The reasonable application of heat treatment technology can significantly improve the comprehensive performance of tungsten -nickel-iron alloys and meet the strict requirements of high-tech fields.

3.3.3 Surface treatment and coating technology

Surface treatment and coating technology are important links in the processing of tungsten-nickel-iron alloys, aiming to improve the corrosion resistance, wear resistance, surface finish and environmental

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adaptability of the alloy. Tungsten -nickel-iron alloys have been widely used in aerospace, military and medical fields due to their high density (16.5-18.75 g/cm³), high hardness (Vickers hardness 250-400) and excellent mechanical properties. However, its surface may be exposed to corrosion, wear or oxidation risks due to processing or environmental factors, so it is necessary to further optimize the performance through surface treatment and coating technology. The following will discuss in detail the surface treatment and coating technology of tungsten -nickel-iron alloys and their key process points.

Surface treatment technology

Surface treatment mainly includes polishing, sandblasting and chemical cleaning processes to improve the surface quality of tungsten nickel iron alloy, remove processing defects and prepare for subsequent coating or application. These technologies can significantly improve the surface finish and corrosion resistance of the alloy to meet the requirements of high precision and harsh environment.

Polishing : Polishing is a common method to improve the surface finish of tungsten -nickel-iron alloys, which can achieve low surface roughness (Ra 0.1-0.2 μm), suitable for medical radiation shielding or aerospace precision parts. Mechanical polishing uses diamond paste or alumina polishing liquid, combined with a high-speed rotating polishing disk (speed 1000-2000 rpm), and the polishing time is 10-30 minutes. Electrochemical polishing is also commonly used for complex-shaped parts, using an acidic electrolyte (such as a sulfuric acid-phosphoric acid mixture) with a current density of 5-10 A/dm² and a processing time of 5-15 minutes. Polishing not only improves the surface appearance, but also reduces microcracks and stress concentration, and improves corrosion resistance and fatigue resistance.

Sandblasting : Sandblasting uses high-pressure airflow to spray abrasives (such as aluminum oxide or glass beads, with a particle size of 50-150 microns) onto the alloy surface to remove oxide layers, burrs or processing marks, while forming a uniform matte surface (Ra 1.6-3.2 μm). The sandblasting pressure is controlled at 0.3-0.6 MPa and the spraying distance is 100-150 mm. Sandblasting can enhance surface roughness and provide better adhesion for subsequent coatings. It is suitable for military armor-piercing cores or industrial wear-resistant parts. Care should be taken to control the sandblasting time (usually 1-3 minutes) to avoid excessive roughness or surface damage.

Chemical cleaning : Chemical cleaning is used to remove surface oil, oxides or processing residues to ensure a clean surface. Common cleaning solutions are dilute acids (such as 5%-10% hydrochloric acid or nitric acid solution) or alkaline solutions (such as sodium hydroxide solution), with a cleaning temperature of 40-60°C and a time of 5-10 minutes. After cleaning, rinse with deionized water and dry in a vacuum or inert gas (such as nitrogen) to prevent secondary oxidation. Chemical cleaning is often used as a pretreatment step before coating to ensure good bonding between the coating and the substrate.

Coating Technology

Coating technology further enhances the corrosion resistance, wear resistance or thermal stability of tungsten nickel iron alloy by applying functional coatings on its surface. Common coating methods

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include electroplating, physical vapor deposition (PVD), chemical vapor deposition (CVD) and thermal spraying, each technology provides different performance improvements for specific application requirements.

Electroplating : Electroplating is commonly used to apply nickel-phosphorus (Ni-P) or nickel-chromium (Ni-Cr) coatings to improve corrosion resistance and surface hardness. Ni-P coatings (containing 8%-12% phosphorus) are applied via an electroless process with a bath temperature of 80-90°C, a pH of 4.5-5.5, a deposition time of 1-2 hours, and a coating thickness of 10-50 microns. Ni-P coatings can reach a hardness of 500-600 HV and have excellent corrosion resistance, making them suitable for counterweights in marine engineering. Ni-Cr coatings are applied via an electroplating process with a current density of 20-40 A/dm² and a coating thickness of 5-20 microns, making them suitable for industrial parts that require high wear resistance. Electroplating requires ensuring that the substrate surface is clean to avoid coating flaking.

Physical Vapor Deposition (PVD) : PVD deposits thin films (such as TiN, CrN or DLC) on the alloy surface by evaporating or sputtering metal/ceramic materials in a vacuum environment, with a thickness of 1-5 microns. The PVD process is carried out at 300-500°C, a vacuum degree of 10⁻³ -10⁻⁴ Pa , and a deposition time of 1-3 hours. The hardness of the TiN coating can reach 2000-2500 HV, which significantly improves the wear resistance and is suitable for military armor-piercing projectile cores or cutting tool surfaces. DLC (diamond-like carbon) coating has a low friction coefficient (0.1-0.2) and excellent corrosion resistance, and is suitable for sliding parts in medical equipment. PVD coatings have strong adhesion, but the equipment cost is relatively high and is suitable for high-precision applications.

Chemical Vapor Deposition (CVD) : CVD deposits a ceramic coating (such as WC or Al₂O₃) on the alloy surface through a chemical reaction with a thickness of 5-10 microns. The process temperature is 800-1000°C and needs to be carried out in an atmosphere containing a carbon or aluminum precursor. The deposition time is 2-4 hours. CVD coatings have extremely high hardness (WC coatings can reach 1500-2000 HV) and high temperature resistance, making them suitable for aerospace high-temperature components or industrial molds. However, high-temperature processes may affect the microstructure of the alloy matrix, and subsequent heat treatment (such as annealing) is required to optimize performance.

Thermal spraying : Thermal spraying (such as plasma spraying) sprays ceramic or metal powder (such as WC-Co or Ni-based alloy) onto the alloy surface through a high-temperature flame flow to form a coating with a thickness of 50-200 microns. Spraying is carried out under the protection of argon or helium. Thermal spray coatings have excellent wear resistance and corrosion resistance and are suitable for industrial wear-resistant parts or counterweights in marine environments, but the coating density is low (about 95%) and may require subsequent machining or heat treatment.

Process control and application

The implementation of surface treatment and coating technology requires strict control of process parameters to ensure the bonding strength and performance stability of the coating and substrate. Before

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surface treatment, oil and oxides need to be removed by ultrasonic cleaning or chemical cleaning. After coating, adhesion tests (such as scratch tests) and hardness tests (such as Vickers hardness testers) need to be performed to verify the quality. The coating thickness needs to be optimized according to application requirements. Too thick may cause peeling, and too thin may not provide sufficient protection. These technologies have significantly improved the application performance of tungsten-nickel-iron alloys. For example, Ni-P electroplating coatings enhance the corrosion resistance of marine engineering counterweights; PVD TiN coatings improve the wear resistance of military armor-piercing projectile cores; CVD WC coatings provide thermal protection for high-temperature aerospace components. The reasonable selection and optimization of surface treatment and coating technologies enable tungsten-nickel-iron alloys to meet diverse and high-performance application requirements.



CTIA GROUP LTD Tungsten Nickel Iron Alloy

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Chapter 4 Quality Control and Inspection of Tungsten-Nickel-Iron Alloy

4.1 Composition Analysis of Tungsten-Nickel-Iron Alloy

Tungsten -nickel-iron alloys are key steps to ensure that their performance meets the stringent requirements of aerospace, military, medical and other fields. Composition analysis is the core part of quality control, which aims to verify whether the chemical composition and microstructure of the alloy meet the design standards. The properties of tungsten -nickel-iron alloys (such as density, strength and corrosion resistance) directly depend on the precise proportions of tungsten (85%-95%), nickel (5%-10%) and iron (2%-5%) and the uniformity of their microstructure. Therefore, chemical composition testing and microstructure analysis are indispensable steps to ensure the stability and reliability of the alloy. The following will discuss the chemical composition testing methods and microstructure analysis techniques in detail.

4.1.1 Chemical composition detection method

Chemical composition testing is used to determine the content of tungsten , nickel, iron and other trace elements in tungsten-nickel-iron alloys to ensure that they meet the target formula (such as 90W-7Ni-3Fe) and related standards (such as ASTM B777). The detection method must have high accuracy and high sensitivity to identify the main components and trace impurities (such as oxygen, carbon, and sulfur). Commonly used chemical composition detection methods include the following:

X-ray fluorescence spectroscopy (XRF)

X-ray fluorescence spectroscopy is a widely used non-destructive analytical technique based on the interaction between X-rays and matter. When a tungsten -nickel-iron alloy sample is irradiated with high-energy X-rays, the atoms on the surface of the sample absorb the X-ray energy, and the inner electrons are excited and jump to high-energy orbits. At this time, the atoms are in an unstable excited state. The outer electrons will quickly fill the vacancies left by the inner electrons. In this process, the atoms will release energy in the form of characteristic fluorescence radiation (i.e., secondary X-rays). Each element has its own unique atomic structure, so the characteristic fluorescence radiation emitted has a specific energy and wavelength. By detecting the energy and intensity of these fluorescence radiations, the types of elements present in the alloy and their content can be determined .

XRF technology has significant advantages in analyzing tungsten -nickel-iron alloys. It can quickly detect the main elements such as tungsten, nickel, and iron in the alloy. Generally, it only takes 1-5 minutes to complete an analysis, which makes it very suitable for online quality control during the production process. It can provide timely feedback on the composition information of the product, making it easier for production personnel to adjust process parameters. In terms of detection accuracy, XRF can reach 0.01%, which is sufficient to meet the needs for most industrial applications. For example, when tungsten-nickel-iron alloys are used to manufacture conventional mechanical parts, XRF can accurately detect whether the content of the main elements meets the standards and ensure the stability

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of product performance .

In terms of sample preparation, XRF requires the sample surface to have a certain degree of flatness, and the sample needs to be polished to a surface roughness of $Ra < 1.6\mu m$. This is because an uneven surface may cause the scattering and absorption of X-rays to become complicated, thus affecting the accuracy of the test results. Through fine polishing, it can be ensured that the X-rays act evenly on the sample surface, so that the detected fluorescence radiation can more accurately reflect the elemental composition inside the sample .

From the equipment perspective, XRF has many types, including handheld and desktop spectrometers. Handheld spectrometers are highly portable and can quickly detect samples on site. They are suitable for preliminary analysis of large workpieces or samples that are inconvenient to transport to the laboratory. Desktop spectrometers usually have higher resolution and stability, can provide more accurate analysis results, and are suitable for in-depth research and quality control of samples in a laboratory environment. Regardless of the type of equipment, its operation is relatively simple and can be operated by personnel with basic training, which further promotes the widespread application of XRF technology .

However, XRF technology is not perfect. It has low sensitivity for detecting trace elements (such as oxygen or carbon). This is because the characteristic X-ray energy of light elements such as oxygen and carbon is low, which is easily interfered by background noise during the detection process, and the fluorescence intensity they produce is relatively weak, making it difficult to accurately detect their content. When analyzing high-purity tungsten-nickel-iron alloys, if it is necessary to accurately determine extremely small amounts of oxygen and carbon impurities , XRF technology may not meet the requirements, and other more sensitive analysis methods are needed .

Inductively coupled plasma atomic emission spectroscopy (ICP-AES)

Inductively coupled plasma atomic emission spectrometry (ICP-AES) is an analytical method based on plasma-excited atomic emission characteristic spectra to detect element content. When analyzing tungsten -nickel-iron alloy, the sample must first be pretreated, that is, the alloy sample is dissolved in an acid solution . The commonly used acid solution is a mixture of nitric acid or hydrochloric acid. The purpose of this step is to convert the metal elements in the alloy into ions so that they can be excited in the plasma later .

The sample solution after dissolution treatment is introduced into the inductively coupled plasma through the injection system . Inductively coupled plasma is generated by coupling high-frequency electric energy to the plasma torch through inductance (induction coil). It looks like a flame and has the characteristics of high temperature (the flame temperature can reach 6000-8000K). After entering the plasma, the sample solution quickly undergoes processes such as evaporation, dissociation, atomization and ionization. Because atoms of different elements have different energy level structures, under the high temperature excitation of plasma, the outer electrons of atoms will jump to high energy level orbits. When these electrons return from high energy levels to low energy levels, they will emit spectra of their

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own characteristic wavelengths .

ICP-AES has high sensitivity to the main elements (tungsten, nickel, iron) and trace impurities (such as sulfur and phosphorus) in tungsten-nickel-iron alloys, and its detection limit can reach ppm level (parts per million). This means that it can detect extremely trace impurity elements in the alloy, which is of great significance for studying the effects of trace impurities on alloy properties. When studying the effects of sulfur and phosphorus impurities on the corrosion resistance of tungsten-nickel-iron alloys, ICP-AES can accurately determine the ppm level of sulfur and phosphorus in the alloy, providing a data basis for further studying the relationship between impurities and corrosion resistance .

However, the sample preparation process of ICP-AES is relatively complicated and time-consuming. The alloy needs to be ground into powder to increase the contact area between the sample and the acid solution and promote the dissolution reaction. The powder sample is then dissolved in the acid solution. This process may take a certain amount of time to ensure that the sample is completely dissolved. The entire sample preparation process usually takes a certain amount of time and effort. In terms of analysis time, it takes about 30-60 minutes to complete an ICP-AES analysis, which is less efficient than the rapid analysis of XRF. However, due to its high sensitivity advantage in detecting trace impurities, ICP-AES is still an indispensable analysis method in laboratory research with high requirements for alloy performance and quality control of high-end products .

Glow Discharge Mass Spectrometry (GD-MS)

Glow discharge mass spectrometry (GD-MS) is a high-end analytical technology suitable for accurate analysis of high-purity materials, especially in the detection of the composition of high-purity tungsten-nickel-iron alloys (such as 99.99% pure tungsten for medical use). Its working principle is based on the glow discharge phenomenon. Low-pressure argon gas is filled between two electrodes and a high voltage is applied to ionize the argon gas to form a glow plasma. In this process, the atoms on the surface of the tungsten -nickel-iron alloy sample to be analyzed, which serves as the cathode, are sputtered out by argon ions in the plasma and peel off from the sample surface into the plasma region .

The sputtered sample atoms are further ionized in the plasma to form positive ions. These positive ions are then introduced into the mass spectrometer and separated and detected according to the mass-to-charge ratio (m/z) of different ions. Since atoms of different elements have different masses, signal peaks will be generated at different positions in the mass spectrometer. By analyzing these signal peaks, not only can the types of elements present in the alloy be determined, but also the content of each element can be accurately determined, including major elements and trace elements, with a detection limit of up to ppb level (parts per billion) .

In terms of sample preparation, GD-MS requires that the sample be prepared into a flat block. This is to ensure that the sample surface can be evenly sputtered by argon ions during the glow discharge process , so that the analysis results are more representative. The analysis time is usually 10-20 minutes. Although it is longer than XRF, considering its high sensitivity detection capability for trace elements and its

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importance in the analysis of high-purity materials, such analysis time is acceptable .

GD-MS equipment is relatively expensive, mainly due to its technical complexity and the high precision requirements for key components such as high-resolution mass spectrometers. However, its high sensitivity and ability to analyze multiple elements simultaneously make it widely used in some high-end application fields that require extremely high alloy purity, such as semiconductor manufacturing, aerospace, and medical industries. In semiconductor manufacturing, the tungsten-nickel-iron alloy used requires extremely high purity to avoid impurities affecting the performance of semiconductor devices. GD-MS can accurately detect ppb-level impurity elements in the alloy to ensure that the quality of the material meets the strict standards of semiconductor manufacturing .

Chemical analysis (wet analysis)

Chemical analysis (wet analysis) is a classic analytical method that separates and quantitatively analyzes elements in alloys through chemical reactions. When analyzing tungsten-nickel-iron alloys, the gravimetric method is often used to determine the tungsten content, and the titration method is often used to determine the nickel and iron contents. Taking the gravimetric determination of tungsten content as an example, the alloy sample is first subjected to a series of chemical reactions to precipitate tungsten in the form of a specific compound. Then, through filtering, washing, drying, and weighing, the mass of the precipitate is accurately measured, and the tungsten content in the alloy is calculated based on the chemical reaction equation and related stoichiometric relationships. For the determination of nickel and iron content, the titration method uses a standard solution of known concentration to react chemically with the nickel and iron ions in the sample solution. The nickel and iron contents are calculated based on the volume of the consumed standard solution by judging the titration endpoint .

The chemical analysis method has high precision, and the error can usually be controlled within $<0.1\%$. This makes it of great application value in some situations where the accuracy of the main component content is extremely high, such as standard sample calibration or controversial detection. When formulating new tungsten-nickel-iron alloy standard samples, it is necessary to determine the content of the main elements extremely accurately. The chemical analysis method can provide reliable data support to ensure the accuracy and authority of the standard samples .

However, chemical analysis methods are complex to operate, requiring professional chemical analysts to have proficient experimental skills and rich experience. The entire analysis process involves multiple chemical reaction steps and strict control of reaction conditions. From sample pretreatment to final result calculation, each step needs to be carefully operated, otherwise it is easy to introduce errors. In addition, this method is time-consuming, and it often takes several hours to complete an analysis. This is because during the reaction process, sufficient time needs to be given for the chemical reaction to fully proceed in order to ensure the accuracy of the analysis results. For example, when determining the tungsten content by weight, the formation of precipitation, washing, and drying steps all take a long time to complete . In terms of detecting trace impurities, chemical analysis methods have certain limitations when used alone. Due to the extremely low content of trace impurities in the alloy, their chemical reaction

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phenomena may not be obvious, and it is difficult to accurately detect them by conventional chemical analysis methods. Therefore, in practical applications, in order to improve the efficiency and accuracy of trace impurity detection, it is usually necessary to combine other more sensitive methods, such as ICP-AES. First, the trace impurities are preliminarily detected and quantitatively analyzed by ICP-AES, and then the main components are accurately determined by chemical analysis methods, so as to fully and accurately understand the composition of tungsten -nickel-iron alloy.

Key points of process control : Chemical composition testing needs to select appropriate methods according to application requirements. For example, aerospace counterweights require tungsten content accurate to $\pm 0.5\%$, which can be met by XRF; medical radiation shielding parts require strict control of impurities, and ICP-AES or GD-MS is recommended. Before testing, ensure that the sample surface is clean to avoid contamination affecting the results. The test results should be compared with the target formula, and the raw materials or process parameters need to be adjusted if the deviation exceeds $\pm 0.2\%$.

4.1.2 Microstructure analysis

Microstructure analysis is used to evaluate the internal organization, phase distribution and defects of tungsten -nickel-iron alloys, which directly affect their mechanical properties (such as tensile strength 800-1000 MPa), corrosion resistance and density ($>99\%$). The microstructure of tungsten -nickel-iron alloys is usually composed of tungsten particles and nickel-iron matrix, and its uniformity, porosity and grain boundary characteristics need to be verified through a variety of analytical techniques.

Metallographic microscope analysis: Metallographic microscope is used to observe the microstructure of alloys. The sample needs to be cut, polished ($Ra < 0.1 \mu m$) and etched with chemical etchants (such as nitric acid-ethanol solution) to reveal the microstructure. The analysis can determine the size and shape of tungsten particles (usually nearly spherical or polygonal) and the uniformity of the distribution of nickel-iron matrix. The magnification is 100-1000 times, and defects such as pores, inclusions or grain boundary cracks can be detected. For example, porosity $>1\%$ may reduce density and require optimization of sintering process. Metallographic analysis is simple to operate and suitable for rapid detection during production.

Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS): SEM provides high-resolution microscopic images (up to 10,000 times magnification) for detailed observation of the interface bonding between tungsten particles and the nickel-iron matrix, particle distribution, and microscopic defects. Combined with EDS, local chemical composition analysis can be performed to detect the uniformity of the distribution of tungsten, nickel, and iron and the enrichment of impurity elements (such as oxygen or carbon). The SEM-EDS analysis time is 30-60 minutes, and the sample needs to be polished and conductively treated (such as carbon plating). This method can identify composition segregation or inclusion problems, such as uneven distribution of the nickel-iron matrix, which may lead to reduced toughness.

X-ray Diffraction (XRD): XRD determines the crystal structure, phase composition and grain size by

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analyzing the X-ray diffraction pattern of the sample. In tungsten -nickel-iron alloy, XRD can confirm the body-centered cubic (BCC) structure of tungsten and the face-centered cubic (FCC) structure of the nickel-iron matrix, and detect the presence of harmful phases (such as oxides or carbides). The analysis time is 1-2 hours, and the sample needs to be ground to a flat surface. XRD can be used to evaluate the effect of heat treatment or sintering process on the microstructure, such as grain growth may reduce strength.

Transmission electron microscopy (TEM): TEM provides sub-nanometer resolution microstructural information for analyzing the interface structure, dislocations, and precipitates between tungsten particles and the nickel-iron matrix. TEM samples need to be prepared by ion thinning, with a thickness of <100 nm and an analysis time of 2-4 hours. TEM is suitable for studying the effects of trace precipitates (such as Ni-Fe compounds) on performance, especially in high-performance applications (such as military armor-piercing cores). The disadvantage is that sample preparation is complex and the cost is high.

Analysis points and applications: Microstructure analysis requires a combination of multiple methods to fully evaluate the quality of the alloy. For example, metallographic microscopy and SEM are used to quickly detect porosity and particle distribution, and XRD and TEM are used to deeply analyze phase structure and interface characteristics. The analysis results should verify the tungsten particle size (10-50 microns), matrix uniformity (deviation <5%) and porosity (<1%). If defects are found (such as porosity >1% or inclusions), it is necessary to optimize the raw material purity or sintering parameters (such as increasing the sintering temperature to 1450-1550°C). Microstructure analysis ensures that tungsten -nickel-iron alloys meet the high performance requirements of aerospace counterweights, medical shielding parts, etc.

4.2 Performance test of tungsten nickel iron alloy

Performance testing is a key part of the quality control of tungsten-nickel-iron alloys, used to verify whether they meet the high performance requirements of aerospace, military, medical and other fields. The properties of tungsten -nickel-iron alloys include mechanical properties (such as strength and toughness), thermal properties (such as thermal expansion coefficient and thermal conductivity), and electrical properties (such as electrical conductivity and resistivity). These properties directly affect the performance of the alloy in high stress, high temperature or electromagnetic environments. Through scientific and rigorous testing methods, the reliability, consistency and compliance with design standards (such as ASTM B777) of the alloy can be ensured. The following will discuss in detail the methods and key points of mechanical performance testing, thermal performance testing and electrical performance testing.

4.2.1 Mechanical properties test

Mechanical property tests are used to evaluate the strength, toughness, hardness and wear resistance of tungsten nickel iron alloys to ensure their performance in high stress environments. Typical tungsten nickel iron alloys (such as 90W-7Ni-3Fe) have a tensile strength of 800-1000 MPa, an elongation of 10%-20% and a Vickers hardness of 250-400 HV. The following are commonly used mechanical property

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test methods:

Tensile testing : Tensile testing is used to measure the tensile strength, yield strength and elongation of alloys, following standards such as ASTM E8. The test samples are processed into standard tensile specimens (such as cylindrical, size $\phi 5\text{ mm} \times 25\text{ mm}$) and tested using a universal testing machine at a tensile rate of 0.5-2 mm/min. The test temperature is usually room temperature (20-25°C), and high-temperature tensile tests (such as 500-800°C) can also be performed to simulate aerospace applications. The results need to verify the tensile strength (target 800-1000 MPa) and elongation (target 10%-20%). Deviations >5% may indicate composition segregation or sintering defects.

Hardness test : Hardness test evaluates the alloy's ability to resist deformation, usually using Vickers hardness (HV) or Brinell hardness (HB) tests, following ASTM E92. The Vickers hardness test uses a diamond indenter, applies a load of 5-10 kgf, holds for 10-15 seconds, and measures the indentation size. Typical hardness values are 250-400 HV, depending on the tungsten content (e.g. 95W-4Ni-1Fe can reach 350-400 HV). Hardness testing must be performed on polished samples ($R_a < 0.2\text{ }\mu\text{m}$), and at least 5 points must be tested to take the average value to ensure consistency of the results. Abnormal hardness values may indicate an uneven microstructure or the presence of inclusions.

Impact toughness test : The impact toughness test is used to evaluate the alloy's resistance to fracture under impact loads. It follows ASTM E23 and uses a Charpy or Izod impact tester. The test specimen is a standard notched specimen ($10 \times 10 \times 55\text{ mm}$, V-notch), and the test temperature is room temperature or low temperature (such as -40°C) to simulate extreme environments. The impact toughness of tungsten-nickel-iron alloys is generally low (10-30 J/cm²), but the increase in nickel content can improve toughness. The test results are used to verify the reliability of the alloy in high impact applications.

Wear resistance test : Wear resistance test evaluates the performance of alloys in friction environment, using pin-on-disc wear test (ASTM G99). The test is carried out on a rotating grinding disc (usually alumina or steel), with an applied load of 10-50 N, a sliding speed of 0.1-1 m/s, and a test time of 10-30 minutes. The amount of wear is measured by mass loss or wear scar volume, and the typical wear rate is <0.01 g/h. Wear resistance is related to hardness and microstructure. Uniform tungsten particle distribution and dense matrix can significantly reduce the wear rate. The test results are used to optimize the performance of aerospace wear-resistant parts or industrial molds.

Key points of testing : Mechanical property testing requires the use of calibrated equipment to ensure that the sample surface is flat ($R_a < 0.2\text{ }\mu\text{m}$) and meets standard dimensions. Test results should be compared with target performance, and deviations should be traced back to the cause through microstructure analysis (such as SEM-EDS). Multiple tests (at least 3 times) should be averaged to improve reliability.

4.2.2 Thermal performance test

Thermal performance tests are used to evaluate the performance of tungsten nickel iron alloys in high

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temperature or thermal cycle environments, including thermal expansion coefficient, thermal conductivity and thermal stability. These properties are critical for high temperature applications such as aerospace counterweights and medical shielding components. The following are commonly used thermal performance test methods:

Coefficient of Thermal Expansion Test : The coefficient of thermal expansion (CTE) test measures the dimensional change of an alloy as the temperature changes, following ASTM E831. Using a thermomechanical analyzer (TMA), the sample (size 5×5×25 mm) is heated to 100-800°C at a heating rate of 5-10°C/min, and the linear expansion is recorded. The CTE of tungsten -nickel-iron alloy is typically $4.5\text{--}5.5 \times 10^{-6} / ^\circ\text{C}$, which is close to pure tungsten ($4.5 \times 10^{-6} / ^\circ\text{C}$). The test needs to be performed in an inert gas (such as argon) to prevent oxidation, and the accuracy requirement is $\pm 0.1 \times 10^{-6} / ^\circ\text{C}$. The results are used to verify the dimensional stability of the alloy in a thermal cycling environment (such as turbine blade counterweights).

Thermal conductivity test : The thermal conductivity test evaluates the thermal conductivity of the alloy, following ASTM E1461, using the laser flash method (LFA). The sample (disc-shaped, $\phi 10\text{ mm} \times 2\text{ mm}$) is tested in the range of room temperature to 1000°C. The laser pulse heats one side of the sample and the infrared detector measures the temperature response on the other side. The thermal conductivity of tungsten -nickel-iron alloy is 100-130 W/m·K, depending on the tungsten content. The test requires polishing the sample ($R_a < 0.1\text{ }\mu\text{m}$) to reduce surface scattering, and the test is repeated 3 times to take the average value. The thermal conductivity results are used to optimize aerospace heat sinks or heat dissipation components of electronic devices.

Thermal stability test : Thermal stability test evaluates the structural and performance stability of alloys at high temperatures, usually performed by differential scanning calorimetry (DSC, ASTM E1269) or high temperature annealing test. In the DSC test, the sample (5-10 mg) is heated to 1200°C under argon protection, with a heating rate of 10°C/min, to detect phase changes or oxidation reactions. Annealing tests are performed in a vacuum furnace (800-1000°C, 2-4 hours), and weight loss ($< 0.1\%$) and microstructural changes (such as metallographic microscope observation) are checked. The high thermal stability of tungsten -nickel-iron alloy (thanks to the high melting point of tungsten at 3410°C) makes it suitable for high temperature applications, and the test results are used to verify its reliability in the nuclear industry or aerospace environment.

Key points of testing : Thermal testing should be conducted in a controlled atmosphere to avoid oxidation affecting the results. Sample preparation should ensure surface flatness and precise dimensions, and test equipment should be calibrated regularly to ensure accuracy (error $< 1\%$). Test results should be compared with target performance, and abnormal values may indicate microstructural defects or composition deviations.

4.2.3 Electrical performance test

Electrical performance testing is used to evaluate the conductivity and resistivity of tungsten -nickel-iron

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alloys, which affect their performance in electronic devices, electromagnetic equipment, or military applications. The conductivity of tungsten -nickel-iron alloys is usually 1.0×10^{-7} - 1.5×10^{-7} S/m, and the resistivity is 6.7×10^{-8} - 1.0×10^{-7} $\Omega \cdot m$. The following are commonly used electrical performance test methods:

Conductivity/resistivity test : Conductivity and resistivity tests are performed using the four-probe method in accordance with ASTM B193. The test specimens are long strips (size 50×5×2 mm) with a surface polished to $R_a < 0.1 \mu m$ to reduce contact resistance. The four-probe device applies a constant current (1-10 mA), measures the voltage drop, and calculates the resistivity. The test is performed at room temperature (20-25°C) and can also be extended to high temperatures (such as 500°C) to evaluate the effect of temperature. The resistivity of tungsten -nickel-iron alloy increases slightly with temperature (temperature coefficient of approximately 0.004/°C), and the test accuracy must reach $\pm 0.1 \times 10^{-8}$ $\Omega \cdot m$. The results are used to verify the performance of the alloy in electrodes or conductive parts.

Surface resistance test : The surface resistance test evaluates the electrical conductivity of the alloy surface and is applicable to components after coating or surface treatment. Using a megohmmeter or surface resistance tester, apply a voltage of 100-500 V and measure the surface resistance (usually $> 10^9 \Omega$). The test needs to be carried out in a dry environment (humidity $< 50\%$) and the sample surface should be clean to avoid contamination. The surface resistance results are used to verify the insulation performance of medical device shielding or electronic components.

Magnetic property test (related to electricity) : The weak ferromagnetism of tungsten -nickel-iron alloy (derived from nickel and iron) may affect its electrical application, and the magnetization intensity needs to be tested by a vibrating sample magnetometer (VSM). The sample (size 5×5×5 mm) is placed in a 0-2 T magnetic field at room temperature, and the saturation magnetization intensity (0.1-0.3 T) is measured. The test time is 10-20 minutes, and the equipment needs to be calibrated to ensure accuracy ($\pm 1\%$). The magnetic property results are used to evaluate the suitability of the alloy in electromagnetic devices, such as electromagnetic shielding counterweights.

Key points of testing : Electrical testing requires ensuring that there is no oxide layer or contamination on the sample surface, and the contact point must be stable to reduce measurement errors. High temperature testing must be performed in an inert gas (such as argon) to prevent oxidation from affecting conductivity. The test results should be compared with the target value. Deviations $> 2\%$ may indicate uneven composition or microscopic defects, which require SEM-EDS or XRD analysis for traceability.

4.2.4 Magnetic performance test

The magnetic performance test of tungsten -nickel-iron alloy is used to evaluate its magnetic properties, which mainly comes from the ferromagnetism of nickel and iron, while tungsten itself is a paramagnetic material. The alloy usually exhibits weak ferromagnetism, and the magnetization intensity (saturation magnetization intensity 0.1-0.3 T) is affected by the nickel (5%-10%) and iron (2%-5%) content. Magnetic performance testing is crucial for the application of aerospace electromagnetic compatibility

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components, military electromagnetic equipment, and medical equipment (such as MRI shielding). The following are commonly used magnetic performance test methods:

Vibrating sample magnetometer (VSM) test : VSM is the main method for measuring the magnetization of alloys and follows ASTM A894. The sample (size 5×5×5 mm or powder) is placed in a 0-2 T magnetic field with a vibration frequency of 40-80 Hz, and the magnetization curve (MH curve) is measured to determine the saturation magnetization, remanence and coercivity. The test is performed at room temperature (20-25°C) or high temperature (such as 500°C), and the analysis time is 10-20 minutes. The saturation magnetization of tungsten -nickel-iron alloy is usually 0.1-0.3 T, and the coercivity is low (<1000 A/m), which is suitable for electromagnetic shielding applications. The test requires calibrated equipment (accuracy ±1%), and the sample surface needs to be polished (Ra<0.1 μm) to reduce interference.

Magnetic permeability test : The magnetic permeability test evaluates the alloy's ability to respond to an external magnetic field. A ring sample (20 mm outer diameter, 10 mm inner diameter, 5 mm thickness) is used, and an AC magnetic field with a frequency of 50 Hz-1 MHz is applied using an LCR meter or a magnetic permeability tester. The relative magnetic permeability of tungsten -nickel-iron alloy is usually 1.1-1.5, reflecting its weak ferromagnetism. The test needs to be carried out in an environment without external magnetic field interference to ensure an accuracy of ±2%. The results are used to verify the suitability of the alloy in electromagnetic equipment, such as magnetic positioning components.

Hysteresis loss test : The hysteresis loss test evaluates the energy loss of the alloy in an alternating magnetic field, using a BH ring tester in accordance with ASTM A927. The sample is in a ring or rod shape, and an alternating magnetic field of 0.1-1 T is applied at a frequency of 50-1000 Hz to measure the hysteresis loop area. The hysteresis loss of tungsten -nickel-iron alloy is low (<10 W/kg), which is suitable for dynamic magnetic field applications. The test time is 15-30 minutes, and the sample temperature needs to be controlled to avoid interference from thermal effects.

Key points of the test : Magnetic testing must ensure that the sample has no surface oxidation or contamination, and the test environment must shield the external magnetic field. The results should be compared with the target value. Deviations > 5% may indicate uneven distribution of nickel and iron, and microstructure analysis is required by SEM-EDS. High-temperature testing must be performed under argon protection to prevent oxidation. The test results are used to optimize the alloy formula (such as adjusting the nickel-iron ratio) to meet the needs of aerospace or military electromagnetic applications.

4.3 Quality Certification and Standards

Quality certification and standards are important guarantees for the performance, reliability and market compliance of tungsten-nickel-iron alloys . China 's national standards provide uniform specifications for the production, testing and application of alloys, covering composition, performance and test methods. Following these standards ensures that the alloys meet the high performance requirements of aerospace, military and medical fields, while facilitating international trade and quality certification. The following

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discusses the Chinese national standards for tungsten -nickel-iron alloys:

4.3.1 Chinese National Standard for Tungsten-Nickel-Iron Alloy

China's national standards (GB standards) provide detailed specifications for the manufacture and testing of tungsten-nickel-iron alloys, mainly referring to GB/T 26036-2010 Heavy Tungsten Alloys and related material standards. These standards specify the chemical composition, mechanical properties, density, microstructure and test methods of the alloy to ensure its quality consistency and application reliability:

Chemical composition : According to GB/T 26036-2010, the tungsten content of tungsten-nickel-iron alloy should be 85%-97%, nickel content 2%-10%, iron content 1%-5%, and the total content of impurities (such as oxygen, carbon, sulfur) <0.1%. The standard requires the use of XRF, ICP-AES or GD-MS to detect the composition with an accuracy of $\pm 0.2\%$ to ensure high density ($16.5-18.75 \text{ g/cm}^3$) and corrosion resistance. For example, 90W-7Ni-3Fe needs to verify the tungsten content of $90 \pm 0.5\%$ to meet the requirements of military armor-piercing cores.

Mechanical properties : The standard stipulates that the tensile strength is $\geq 800 \text{ MPa}$, the elongation is $\geq 10\%$, and the Vickers hardness is 250-400 HV. The tensile test is carried out in accordance with GB/T 228.1-2010, and the hardness test is carried out in accordance with GB/T 231.1-2018. The results must meet the requirements of aerospace counterweights (toughness first) or military components (strength first). If the deviation is $>5\%$, the sintering process needs to be adjusted.

Density and microstructure : Density requirement is $16.5-18.75 \text{ g/cm}^3$, density $\geq 99\%$, tested by Archimedes method (GB/T 1423-1996). Microstructure should be uniform, tungsten particle size 10-50 microns, porosity $<1\%$, analyzed by metallographic microscope or SEM. Abnormal porosity may indicate insufficient sintering temperature (needs to be increased to $1450-1550^\circ\text{C}$).

Test methods : The standard requires the use of standardized test methods, such as XRF, ICP-AES (composition), tensile test (mechanical properties), TMA (thermal expansion coefficient $4.5-5.5 \times 10^{-6} / ^\circ\text{C}$), LFA (thermal conductivity $100-130 \text{ W/m}\cdot\text{K}$). The testing equipment needs to be calibrated regularly, and the test data needs to be recorded and meet the standard tolerances.

Application and certification : GB/T 26036-2010 is applicable to aerospace counterweights, military armor-piercing cores, and medical radiation shielding parts. Products that meet the standard can obtain quality certification (such as ISO 9001 or GJB 9001C military certification) to facilitate market promotion and international trade. Manufacturers are required to provide test reports to prove that the alloy properties meet the standard requirements.

4.3.2 International Standards for Tungsten-Nickel-Iron Alloy

International standards provide global uniform specifications for the production, testing and application of tungsten-nickel-iron alloys, ensuring consistency in quality, performance and cross-border trade.

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Tungsten -nickel-iron alloys are widely used in aerospace, military and medical fields due to their high density (16.5-18.75 g/cm³), high strength (800-1000 MPa) and excellent corrosion resistance. The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have developed relevant standards covering chemical composition, mechanical properties, density and test methods. The following are the main international standards:

Tungsten alloys for aerospace : This standard specifies the technical requirements for tungsten-based alloys (including tungsten -nickel-iron alloys) for aerospace. The chemical composition requires tungsten content of 85%-97%, nickel 2%-10%, iron 1%-5%, and the total content of impurities (such as oxygen, carbon, and sulfur) <0.1%. Mechanical properties require tensile strength ≥ 700 MPa, elongation $\geq 10\%$, and Vickers hardness 250-400 HV. The density range is 16.5-18.75 g/cm³, and the density is $\geq 99\%$. Test methods include XRF or ICP-AES (composition analysis), tensile test (ASTM E8), hardness test (ISO 6507-1) and metallographic analysis (ISO 643). The standard applies to counterweights and balance blocks to ensure dimensional stability and corrosion resistance.

ASTM B777-15 (High-density tungsten alloy) : ASTM B777 is an international standard for tungsten-nickel-iron alloys, which are divided into four categories (Class 1-4), corresponding to tungsten content of 90%-97% and density of 16.85-18.75 g/cm³. For example, Class 1 (90W-7Ni-3Fe) requires density ≥ 17.0 g/cm³, tensile strength ≥ 758 MPa, and elongation $\geq 5\%$. Test methods include Archimedes method (density), tensile test (ASTM E8), hardness test (ASTM E92), and SEM-EDS (microstructure). The standard requires verification of impurity content (oxygen <0.05%) to ensure corrosion resistance and radiation resistance, and is suitable for military armor-piercing cores and medical shielding parts.

ISO 9001:2015 (Quality Management System) : Although not specific to WNITROGEN, this standard requires manufacturers to establish a quality management system to ensure consistency in production processes and product performance. WNITROGEN production must comply with ISO 9001 certification, including standardized management of raw material procurement, sintering processes and performance testing. Certification ensures product traceability and meets international market requirements.

Application and significance : International standards such as ISO 20886 and ASTM B777 provide a technical basis for the global trade of tungsten-nickel-iron alloys, ensuring their reliability in aerospace (such as counterweights), military (such as armor-piercing cores) and medical (such as radiation shielding). Manufacturers are required to provide test reports that meet the standards to verify the composition, performance and microstructure, and deviations (such as tungsten content $\pm 0.5\%$) need to be corrected through process optimization.

4.3.3 Tungsten-nickel-iron alloy standards in Europe, America, Japan, South Korea and other countries around the world

Different countries and regions have developed regional standards for tungsten-nickel-iron alloys based on their industrial needs and technical characteristics. These standards are usually compatible with international standards (such as ASTM B777 or ISO 20886), but focus on certain details to adapt to local

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application scenarios (such as military, aviation or medical). The following are the tungsten-nickel-iron alloy standards of major countries such as Europe, America, Japan and South Korea:

United States (ASTM B777-15 and MIL-T-21014D) : The United States uses ASTM B777-15 as the main standard, which specifies the classification (Class 1-4), composition (tungsten 90%-97%), density (16.85-18.75 g/cm³) and performance (tensile strength 758-930 MPa) of tungsten-nickel-iron alloys in detail. The military industry also refers to MIL-T-21014D (military specification), which requires stricter impurity control (oxygen <0.03%, carbon <0.02%) and mechanical properties (elongation ≥8%) to meet the needs of armor-piercing cores and aviation counterweights. Test methods include ICP-AES (composition), tensile testing (ASTM E8) and metallographic analysis (ASTM E45). The US standard emphasizes high performance and reliability and is widely used in the defense industry.

Europe (EN 10204 vs. DIN) : Europe uses EN 10204 (Metallic Material Inspection Certificate) to regulate the quality certification of tungsten -nickel-iron alloys, requiring a 3.1 or 3.2 type test report to prove that the composition and performance meet the design requirements. German DIN standards (such as DIN EN ISO 20886) are consistent with ISO standards, emphasizing tungsten content of 85%-97%, density of 16.5-18.5 g/cm³, and tensile strength ≥700 MPa. European standards focus on corrosion resistance and microstructural uniformity (porosity <1%), and test methods include XRF, SEM-EDS, and TMA (thermal expansion coefficient $4.5-5.5 \times 10^{-6} / ^\circ \text{C}$). These standards apply to aerospace counterweights and medical radiation shielding parts.

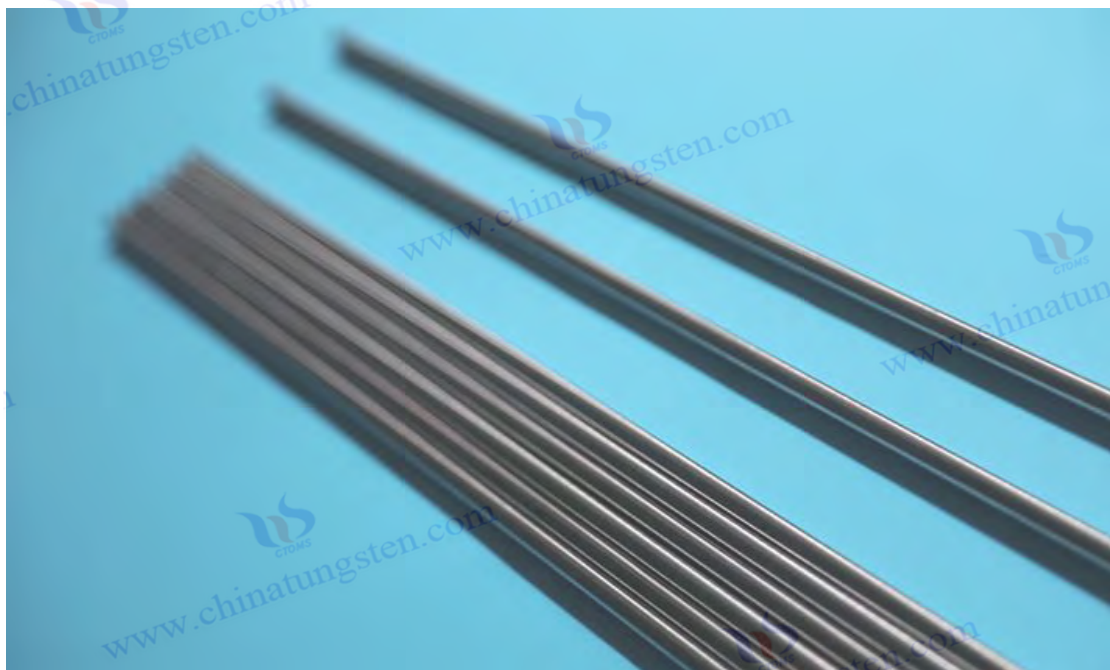
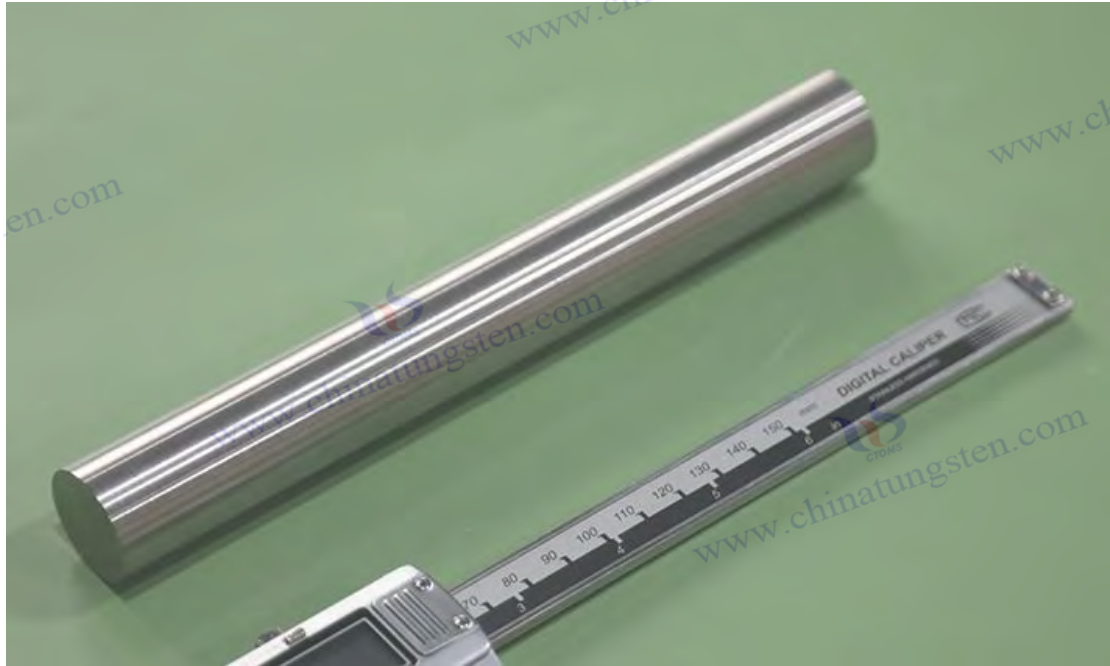
Japan (JIS H 4463) : Japanese Industrial Standard JIS H 4463 specifies the technical requirements for high-density tungsten alloys, which are applicable to tungsten -nickel-iron alloys. The standard requires a tungsten content of 88%-95%, an adjustable nickel-iron ratio, a density of 16.5-18.5 g/cm³, a tensile strength ≥750 MPa, and an elongation ≥10%. Test methods include ICP-AES (composition), tensile testing (JIS Z 2241) and hardness testing (JIS Z 2245). The Japanese standard emphasizes high-precision processing and surface quality (Ra<0.8 μm), which is suitable for electronic device counterweights and medical equipment. Japanese manufacturers often combine ISO 9001 certification to ensure that their products meet international market requirements.

South Korea (KS D 9502) : The Korean standard KS D 9502 specifies the composition and properties of high-density tungsten alloys with a tungsten content of 85%-95%, a density of 16.5-18.75 g/cm³, a tensile strength ≥700 MPa, and a Vickers hardness of 250-400 HV. The test methods are similar to ASTM B777, including the Archimedes method (density), tensile testing, and XRD (microstructure). The Korean standard focuses on wear resistance and thermal stability and is suitable for industrial molds and aerospace components. South Korea also requires compliance with the RoHS directive, limiting the content of harmful impurities (such as lead) to meet environmental requirements.

Other countries : [...]: Countries such as Russia and India usually refer to ASTM or ISO standards, but may have local adjustments. For example, Russia's GOST standard requires composition and performance specifications similar to ASTM B777, but emphasizes low-temperature toughness testing (-50°C) to accommodate extreme environmental applications.

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Comparison and application : European and American standards (such as ASTM B777, EN 10204) focus more on the high performance requirements of military and aerospace, while Japanese and Korean standards (JIS H 4463, KS D 9502) emphasize precision processing and environmental protection. Standards in all countries require strict composition (tungsten $\pm 0.5\%$) and performance testing (tensile strength $\pm 5\%$), and the testing methods include XRF, ICP-AES and SEM-EDS. Manufacturers need to select the corresponding standards according to the target market to ensure product compliance .



CTIA GROUP LTD Tungsten Nickel Iron Alloy

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CTIA GROUP LTD
Tungsten Nickel Iron Alloy Introduction

1. Overview of Tungsten Nickel Iron Alloy

Tungsten-nickel-iron alloy is a high-density material with tungsten as the primary component and nickel and iron added as binder phases. Known for its excellent physical and chemical properties, it is widely used in aerospace, military, medical, nuclear industries, and civilian fields. CTIA GROUP LTD offers tungsten-nickel-iron alloy products, including alloy rods, counterweights, radiation shields, and phone vibrators, tailored for various applications.

2. Features of Tungsten Nickel Iron Alloy

High Density: Typically ranges from 16.5 to 18.75 g/cm³.

High Strength: Tensile strength ranges from 700 to 1000 MPa.

Other Characteristics: Exhibits strong radiation absorption, high thermal conductivity, low thermal expansion coefficient, good electrical conductivity, plasticity, weldability, and processability.

3. Tungsten-Nickel-Iron Alloy Grades

Grade	Class 1	Class 1	Class 2	Class 2	Class 3	Class 3	Class 4
Composition (%)	90W 7Ni3Fe	91W 6Ni3Fe	92W 5Ni3Fe	93W 4Ni3Fe	95W 3Ni2Fe	96W 3Ni1Fe	97W 2Ni1Fe
Density (g/cm ³)	17.1	17.25	17.50	17.60	18.10	18.30	18.50
Heat Treatment	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering
Tensile Strength (PSI)	900~1000		900~1100		920~1100		
Elongation (%)	18~29	17~27	16~26	16~24	10~22	8~20	6~13
Hardness (HRC)	24~28	25~29	25~29	26~30	27~32	28~34	28~36

4. Production Methods for Tungsten Nickel Iron Alloy

The powder metallurgy process involves first mixing tungsten powder, nickel powder, and iron powder; then ball milling and sieving; followed by shaping the mixed powder into blanks using hot pressing, hot isostatic pressing, or vacuum sintering techniques; and finally improving the alloy's microstructure and properties through heat treatments such as annealing or quenching.

5. Applications of Tungsten Nickel Iron Alloy

In the medical field, tungsten-nickel-iron alloy serves as radiation shields, radiation source containers, collimators, isotope containers, and syringe shields. In scientific research, tungsten alloy is used as heat sinks and for oil drilling and mineral resource exploration.

6. Purchasing Information

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Chapter 5 Application Fields of Tungsten Nickel Iron Alloy

5.1 Application of tungsten-nickel-iron alloy in the aerospace industry

Tungsten -nickel-iron alloy is widely used in the aerospace industry due to its high density, excellent mechanical properties, corrosion resistance and thermal stability. The alloy can meet the demand for high-performance materials in the aerospace field, especially in scenarios that require high-density counterweights or high-temperature environments. The unique properties of tungsten -nickel-iron alloy make it a key material in equipment such as aircraft, spacecraft and satellites. The following will discuss its application in counterweight materials and high-temperature resistant components in detail.

5.1.1 Balancing materials

Tungsten -nickel-iron alloy is an ideal choice for counterweight materials in the aerospace field due to its high density. Counterweights are used to adjust the center of gravity of aircraft, ensure flight stability or optimize dynamic performance. Compared with traditional counterweight materials such as lead, tungsten-nickel-iron alloy can provide the required mass in a smaller volume, while having better mechanical strength and environmental friendliness, meeting the requirements of aerospace for lightweight and high performance.

Application scenarios : Tungsten -nickel-iron alloys are widely used in aircraft ailerons, rudders, elevators, and helicopter rotor counterweights. In commercial aircraft, counterweights are used to adjust wing balance and ensure aerodynamic stability during flight. In spacecraft, such as satellites or space stations, counterweights are used to correct orbital attitude or stabilize rotating parts.

Performance advantages : High density enables tungsten-nickel-iron alloy to achieve efficient weight balance and reduce the volume and weight of components. The low thermal expansion characteristics of the alloy ensure that it remains dimensional stable under temperature changes (such as low temperature or high temperature environment at high altitude) and avoids deformation caused by thermal stress. Excellent strength and toughness enable it to withstand vibration and impact loads during flight. In addition, the corrosion resistance of the alloy makes it suitable for long-term exposure to moisture or salt spray environments, such as high altitude or over the ocean.

Processing and quality requirements : Counterweights are usually manufactured by powder metallurgy, combined with machining to achieve high precision. Surface treatment can enhance corrosion resistance. Quality control needs to ensure uniform density and consistent microstructure of counterweights to ensure stable performance.

5.1.2 High temperature resistant parts

Tungsten nickel iron alloy makes it a preferred material for high temperature resistant components in the aerospace industry. The high melting point and thermal stability of tungsten, combined with the oxidation

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resistance and toughness of nickel and iron, enable the alloy to maintain structural integrity and mechanical properties in high temperature environments. Such components have important applications in aerospace engines, spacecraft hot end components and propulsion systems.

Application scenarios : Tungsten -nickel-iron alloys are often used in turbine blade counterweights, nozzle components or hot end balance blocks in aircraft engines . In turbofan engines, the alloy is used as a blade counterweight to optimize rotational balance and withstand the impact of high-speed rotation and high-temperature gas. In spacecraft propulsion systems, the alloy is used to manufacture supports for nozzles or combustion chamber components, which need to withstand instantaneous high temperatures and thermal cycle stresses.

Performance advantages : The high thermal conductivity of the alloy can quickly disperse heat and prevent local overheating, which is suitable for thermal management in high-temperature environments. Its low thermal expansion characteristics ensure that the components remain dimensional stable when they are rapidly heated or cooled, avoiding thermal stress cracks. The oxidation resistance of nickel enables the alloy to resist oxidation corrosion in hot air and extend its service life. The strength and toughness of the alloy enable it to withstand vibration and mechanical stress.

Processing and quality requirements : High temperature resistant parts are manufactured by powder metallurgy combined with hot isostatic pressing to ensure microstructural uniformity and high density. Machining requires the use of high hardness tools, and surface treatments such as coatings can further improve wear resistance and high temperature resistance. Quality control requires verification of the performance stability and oxidation resistance of the parts in high temperature environments.

5.2 Defense and Military

Tungsten -nickel-iron alloy has important applications in the defense and military fields due to its high density (16.5-18.75 g/cm³), excellent mechanical properties (tensile strength 800-1000 MPa, elongation 10%-20%), corrosion resistance and thermal stability. This alloy can meet the needs of modern military equipment for high-performance materials, especially in scenarios that require high penetration or high protection capabilities. The unique properties of tungsten -nickel-iron alloy make it an ideal material for key components such as armor-piercing projectiles and protective armor. Its high density and strength can provide excellent performance under extreme conditions. The following will discuss in detail the application of tungsten -nickel-iron alloy in armor-piercing projectile materials and protective armor.

5.2.1 Armor-piercing materials

Tungsten -nickel-iron alloy has become the first choice for the core material of modern armor-piercing ammunition due to its high density, excellent strength and moderate toughness. Armor-piercing ammunition is used in military equipment such as tanks, anti-tank weapons and ship-borne artillery, and is designed to penetrate enemy armored targets such as tank armor or armored vehicles. The high density of tungsten -nickel-iron alloy gives the core extremely high kinetic energy, while its good mechanical properties ensure that the core maintains structural integrity during high-speed impact, thereby achieving

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excellent armor-piercing effect.

Application scenarios : Tungsten -nickel-iron alloys are widely used as core materials for kinetic armor-piercing projectiles (APFSDS, Armor-Piercing Fin-Stabilized Discarding Sabot). For example, tank shells often use tungsten -nickel-iron alloy cores, which have high density and strength and can penetrate hundreds of millimeters thick rolled homogeneous armor (RHA). In anti-tank missiles or shipborne artillery, tungsten-nickel-iron alloy cores are used to counter modern composite armor and reactive armor, providing reliable penetration. The typical formula is 90W-7Ni-3Fe or 93W-5Ni-2Fe to balance density, strength and toughness.

Performance advantages : The high density of tungsten -nickel-iron alloy ($17.0-18.5 \text{ g/cm}^3$) enables the core to have extremely high kinetic energy when fired at high speed (initial velocity can reach $1500-1800 \text{ m/s}$), enhancing penetration. Its high tensile strength ($800-1000 \text{ MPa}$) and moderate toughness (elongation $10\%-20\%$) ensure that the core is not easy to break or deform excessively when hitting the armor, and can effectively transfer kinetic energy to the target. The thermal conductivity of the alloy ($100-130 \text{ W/m}\cdot\text{K}$) helps to disperse the instantaneous high temperature generated by the impact and prevent the core from softening or melting. In addition, the corrosion resistance of the alloy (thanks to the oxidation resistance of nickel) enables it to be stored for a long time in a humid or salt spray environment, which is suitable for the diverse environmental requirements of military equipment.

Processing and quality requirements : Armor-piercing cores are usually prepared by powder metallurgy combined with hot isostatic pressing to ensure density $>99.5\%$ and microstructural uniformity. Machining uses high-hardness CBN tools with a machining accuracy of $\pm 0.01 \text{ mm}$ to ensure geometric consistency of the core. Heat treatment can further increase the hardness (Vickers hardness $350-400 \text{ HV}$) and enhance penetration. Quality control must comply with ASTM B777 or MIL-T-21014D standards, verifying density deviation $<0.2 \text{ g/cm}^3$, porosity $<1\%$, and ensuring performance consistency through tensile testing and metallographic analysis. Surface coatings (such as PVD TiN) can improve wear resistance and extend the life of the core in high-speed friction.

5.2.2 Protective armor

Tungsten -nickel-iron alloy in protective armor is mainly reflected in the high-density shielding layer and the reinforcement components of composite armor. It is widely used in the protection systems of tanks, armored vehicles and ships. Protective armor needs to withstand the test of high-speed projectiles, explosive shocks and extreme environments. The high density, strength and toughness of tungsten-nickel-iron alloy enable it to effectively absorb and disperse impact energy and improve the protective performance of armor. In addition, the corrosion resistance and thermal stability of the alloy make it suitable for long-term deployment in harsh environments.

Application scenarios : Tungsten -nickel-iron alloys are often used in high-density layers in composite armor, combined with ceramics, steel or polymer materials to form multi-layer protective structures. For example, in the composite armor of main battle tanks (such as the M1A2 Abrams), tungsten-nickel-iron

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alloys are used as reinforcement layers to absorb the impact energy of kinetic energy penetrators or armor-piercing shells (HEAT). In armored vehicles or ships, the alloy is used to manufacture shielding plates in key areas to protect occupants and equipment from shrapnel or explosion impact. The typical formula is 90W-7Ni-3Fe, with a density of 17.0-18.0 g/cm³, providing excellent protection.

Performance advantages : The high density of the alloy (16.5-18.75 g/cm³) enables it to effectively absorb the kinetic energy of the projectile, slow down the penetration speed, and enhance the protective efficiency of the armor. Its high tensile strength (800-1000 MPa) and toughness (elongation 10%-20%) ensure that the armor is not easy to break or peel off under high-speed impact and can withstand multiple blows. Thermal conductivity (100-130 W/m·K) helps to disperse the instantaneous high temperature generated by explosion or impact, preventing local softening or ablation. The low thermal expansion coefficient of the alloy ($4.5-5.5 \times 10^{-6} / ^\circ \text{C}$) ensures dimensional stability and avoids cracks in thermal cycles or explosive environments. Corrosion resistance (thanks to the NiO protective layer of nickel) makes it suitable for use in marine or humid environments, such as ship armor.

Processing and quality requirements : Protective armor parts are manufactured by powder metallurgy combined with hot isostatic pressing to ensure density >99.5% and microstructural uniformity. Machining uses carbide tools or electrical discharge machining (EDM) to achieve complex shapes and high precision (tolerance ± 0.02 mm). Heat treatment can eliminate internal stress and improve toughness. Quality control must comply with MIL-T-21014D or ASTM B777 standards to verify density, strength and porosity (<1%). Surface treatment (such as CVD WC coating or Ni-P electroplating) can enhance wear resistance and corrosion resistance and extend the life of the armor. Microstructural analysis (such as SEM-EDS) is used to detect tungsten particle distribution and matrix uniformity to ensure protective performance.

5.3 Application of Tungsten Nickel Iron Alloy in Medical Field

Tungsten -nickel-iron alloy has important applications in the medical field due to its high density, excellent radiation resistance, good mechanical properties (tensile strength 800-1000 MPa, elongation 10%-20%) and corrosion resistance. Especially in scenarios where high-energy radiation needs to be shielded or precision parts need to be manufactured, tungsten-nickel-iron alloy can meet the needs of medical equipment for high-performance materials. Its high density and radiation resistance make it an ideal choice for shielding components of CT/MRI equipment and collimators of radiotherapy equipment, significantly improving the safety and precision of the equipment. The following will discuss its specific applications in these two aspects in detail.

5.3.1 CT/MRI equipment shielding components

Tungsten -nickel-iron alloys are widely used as shielding components in CT (computed tomography) and MRI (magnetic resonance imaging) equipment to protect patients, medical staff and equipment from the radiation effects of X-rays or gamma rays. CT equipment uses X-ray imaging, and although MRI equipment mainly uses magnetic fields, its auxiliary systems may involve radiation sources, so efficient

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shielding materials are required. The high density and radiation resistance of tungsten -nickel-iron alloys enable it to effectively attenuate high-energy radiation, while its mechanical properties and corrosion resistance ensure the long-term reliability of shielding components.

Application scenarios : In CT equipment, tungsten-nickel-iron alloys are used to manufacture radiation shields, detector shielding plates, and shielding rings around X-ray tubes to prevent radiation leakage. In MRI equipment, the alloy is used to shield auxiliary radiation sources (such as radioactive markers) or electromagnetic interference to ensure magnetic field uniformity. The typical formula is 95W-4Ni-1Fe, which can provide excellent shielding effect in a small volume due to its high density ($18.0\text{-}18.5\text{ g/cm}^3$), meeting the compact design requirements of medical equipment.

Performance advantages : Tungsten's high atomic number ($Z=74$) and high density make it perform well in the photoelectric effect and Compton scattering, and it can effectively absorb X-rays and gamma rays. Its shielding efficiency far exceeds that of traditional materials such as lead (density 11.34 g/cm^3). The alloy's low thermal expansion coefficient ($4.5\text{-}5.5\times 10^{-6}\text{ / }^{\circ}\text{C}$) ensures dimensional stability under the heat generated by the operation of the equipment, avoiding deformation that affects the shielding performance. Its high strength ($800\text{-}1000\text{ MPa}$) and moderate toughness (elongation $10\%\text{-}20\%$) enable shielding components to withstand equipment vibration and mechanical stress. Nickel's oxidation resistance and corrosion resistance (forming a NiO protective layer) ensure the long-term stability of the components in sterilized or humid environments. In addition, the alloy is non-toxic and environmentally friendly, superior to lead-based materials, and meets the strict safety requirements in the medical field.

Processing and quality requirements : Shielding components are manufactured by powder metallurgy (liquid phase sintering, $1450\text{-}1550^{\circ}\text{C}$) combined with hot isostatic pressing (HIP, $1200\text{-}1400^{\circ}\text{C}$, $100\text{-}200\text{ MPa}$) to ensure density $>99.5\%$ and microstructural homogeneity. Machining (such as turning, milling) requires the use of CBN tools to achieve high precision (tolerance $\pm 0.01\text{ mm}$) and surface finish ($Ra < 0.4\text{ }\mu\text{m}$). Surface treatment (such as Ni-P plating or polishing) can further improve corrosion resistance and aesthetics. Quality control must comply with ISO 20886 or ASTM B777 standards to verify density, porosity ($<1\%$) and radiation resistance, and XRF or ICP-AES to detect composition. Microstructural analysis ensures that the tungsten particles are evenly distributed without inclusions or pores.

Technical challenges and optimization : The high hardness of tungsten -nickel-iron alloy (Vickers hardness $350\text{-}400\text{ HV}$) increases the difficulty of processing, and tools and cutting parameters need to be optimized to reduce costs. In MRI equipment, the weak ferromagnetism of the alloy (magnetization intensity $0.1\text{-}0.3\text{ T}$) needs to be strictly controlled to avoid interfering with the uniformity of the magnetic field. The magnetic properties can be optimized by reducing the iron content (such as $1\%\text{-}2\%$) or heat treatment. In the future, additive manufacturing (such as SLM) can realize shielding components with more complex shapes, further improving design flexibility and production efficiency.

5.3.2 Collimators for radiotherapy equipment

Tungsten -nickel-iron alloy is widely used as collimator material in radiotherapy equipment to accurately

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control the direction and range of radiation beams to protect healthy tissues and improve treatment effects. Radiotherapy equipment (such as linear accelerators) use high-energy X-rays or gamma rays to treat tumors, and collimators must have extremely high radiation resistance and precision processing performance. The high density and mechanical properties of tungsten -nickel-iron alloy enable it to meet these stringent requirements, making it the preferred material for collimators in radiotherapy equipment.

Application scenarios : In linear accelerators, tungsten-nickel-iron alloys are used to make multi-leaf collimators (MLCs) and fixed collimators. Multi-leaf collimators consist of dozens of movable alloy leaves that can dynamically adjust the shape of the radiation beam to fit the contour of the tumor. Fixed collimators are used to limit the radiation area and protect surrounding healthy tissues. The typical formula is 95W-4Ni-1Fe or 97W-2Ni-1Fe, which can effectively shield radiation and reduce the volume of the collimator due to its high density (18.0-18.75 g/cm³).

Performance advantages : The high density of the alloy and the high atomic number of tungsten enable it to efficiently absorb high-energy radiation, reduce scattering and leakage, and ensure the accuracy of the radiation beam. Its high strength (800-1000 MPa) and toughness (elongation 10%-20%) ensure that the collimator blades are not easily deformed or broken during rapid movement or long-term use. The low thermal expansion coefficient ($4.5-5.5 \times 10^{-6} / ^\circ \text{C}$) ensures that the collimator maintains geometric accuracy under the heat generated by the operation of the radiotherapy equipment. The corrosion resistance of the alloy (thanks to the oxidation resistance of nickel) enables it to resist the influence of disinfectants and humid environments, extending its service life. Compared with lead, tungsten-nickel-iron alloy is non-toxic and environmentally friendly, meeting the safety standards of medical equipment.

Processing and quality requirements : The collimator is manufactured by powder metallurgy combined with hot isostatic pressing to ensure a density of >99.5% and a non-porous structure. Precision machining is used to manufacture blades with complex shapes, with tolerances of ± 0.005 mm and surface roughness $R_a < 0.2 \mu\text{m}$ to ensure precise control of the radiation beam. Heat treatment can eliminate processing stress and improve toughness. Surface coatings can enhance wear and corrosion resistance. Quality control must comply with ISO 13485 or ASTM B777 standards to verify composition, density and microstructure, and confirm shielding performance through X-ray transmission testing.

Technical challenges and optimization : The high precision requirements of the collimator increase the difficulty of processing, and advanced equipment (such as laser cutting or additive manufacturing) must be used to reduce costs. The weak ferromagnetism of the alloy may cause slight interference in high magnetic field environments, and the formula needs to be optimized or non-magnetic coatings need to be used. In the future, 3D printing technology can realize the customized production of multi-leaf collimators, improve design flexibility and treatment accuracy. The application of tungsten -nickel-iron alloy in radiotherapy collimators has significantly improved the safety and effectiveness of radiotherapy.

5.3.3 Precision medical devices

Tungsten -nickel-iron alloy has important applications in precision medical devices due to its high density,

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excellent mechanical properties and biocompatibility. Precision medical devices usually require high-precision, small-volume and high-reliability materials to meet the performance requirements of diagnostic or therapeutic equipment in complex environments. The high density of tungsten -nickel-iron alloy enables it to provide sufficient mass or shielding effect in a small volume, while its strength and corrosion resistance ensure the long-term stability of the device.

Application scenarios : Tungsten -nickel-iron alloys are used to manufacture small counterweights, shielding components or positioning elements in medical diagnostic equipment. For example, in endoscopes or ultrasound equipment, the alloys are used as micro-counterweights or shielding components to ensure the stability and accuracy of the equipment during complex operations. In radioisotope therapy equipment, the alloys are used to manufacture small shielding containers to protect medical staff from radiation.

Performance advantages : The high density of the alloy allows for efficient mass distribution or radiation shielding in a limited space, making it suitable for miniaturized design. Its high strength and toughness enable the device to withstand vibration or mechanical stress during operation, ensuring that it will not deform or break during long-term use. The low thermal expansion property ensures that the device maintains dimensional stability under changes in body temperature or equipment operating temperature. The corrosion resistance of the alloy enables it to resist erosion by disinfectants or body fluids, extending the life of the device. In addition, the alloy is non-toxic and environmentally friendly, meeting the biosafety requirements of medical devices.

Processing and quality requirements : Precision medical devices are manufactured by powder metallurgy combined with hot isostatic pressing to ensure high density and microstructural uniformity. Precision machining (such as EDM or laser cutting) is used to manufacture complex shapes with micron-level tolerances and extremely high surface finish to reduce friction and wear. Heat treatment eliminates processing stresses and improves toughness. Surface treatments (such as polishing or electroless nickel plating) enhance corrosion resistance and biocompatibility. Quality control verifies composition consistency, density uniformity, and defect-free structure to ensure device reliability in medical environments.

5.3.4 Surgical robot joint counterweights

Tungsten -nickel-iron alloy is used as joint weight material in surgical robots to optimize the robot's motion balance and operation accuracy. Surgical robots (such as minimally invasive surgical systems) require high-precision motion control and stable mechanical properties. The weight components play a role in balancing gravity and improving positioning accuracy in joints or robotic arms. The high density and mechanical properties of tungsten -nickel-iron alloy make it an ideal weight material.

Application scenarios : In surgical robots, tungsten-nickel-iron alloys are used for joint weights or robot arm balances to ensure the stability of the robot when performing delicate operations such as suturing or cutting. For example, in minimally invasive surgical robot systems, alloy weights are used to adjust the

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dynamic balance of the robot arm, reduce vibration and improve surgical precision. In orthopedic or neurosurgery robots, weights help maintain the stability and control of the device during complex movements.

Performance advantages : The high density enables the alloy to provide sufficient counterweight effect in a small volume, optimize the weight distribution of the robot joints, and reduce the energy consumption of the drive system. Its high strength and toughness ensure that the counterweight does not deform or fatigue fracture during rapid movement or frequent operation. The low thermal expansion characteristics ensure that the counterweight remains dimensional stable under temperature changes in the operating room or heat from equipment operation. The corrosion resistance of the alloy enables it to resist chemical erosion by disinfectants and cleaning processes, making it suitable for long-term use. In addition, the weak ferromagnetism of the alloy has been optimized so that it will not interfere with the electromagnetic system of the surgical robot.

Processing and quality requirements : Joint weights are manufactured by powder metallurgy combined with hot isostatic pressing to ensure high density and non-porous structure. Precision machining (such as five-axis CNC or EDM) is used to manufacture complex shapes with tolerances controlled in the micron range, and the surface needs to be polished to a high finish to reduce friction. Heat treatment can improve toughness, and surface coatings (such as DLC) enhance wear and corrosion resistance. Quality control needs to verify density uniformity, mechanical properties and microstructure to ensure the stability of the weight in dynamic operation.

Technical challenges and optimization : Processing tiny counterweights requires high-precision equipment, which increases production costs, and the process needs to be optimized to improve efficiency. The magnetism of the alloy needs to be strictly controlled to avoid interference with robot sensors or electromagnetic systems, which can be solved by reducing the iron content or using non-magnetic coatings. Additive manufacturing technology can be used to customize the production of complex counterweights and improve design flexibility.

5.3.5 Micro-weights for interventional therapy

Tungsten -nickel-iron alloys are used as micro-weights in interventional treatments and are widely used in catheters, guidewires or implantable medical devices to improve the controllability and positioning accuracy of the equipment. Interventional treatments (such as cardiovascular stent implantation or neurointerventional surgery) require miniaturized, high-precision devices, and weights are used to adjust the balance of the device or provide tactile feedback to help doctors operate accurately. The high density and biocompatibility of tungsten -nickel-iron alloys make them the preferred material for such applications.

Application scenarios : In cardiovascular interventional treatment, tungsten-nickel-iron alloys are used for micro-weights at the tip of catheters to optimize the balance and flexibility of catheters and facilitate doctors' navigation within blood vessels. In neurointerventional surgery, alloy weights are used for

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guidewires or microprobes to help accurately reach the target location. The alloy can also be used for weight components of implantable devices, such as balance parts for pacemakers or neurostimulators.

Performance advantages : High density enables the alloy to provide sufficient mass in a small volume, optimize the weight distribution of the device, and improve controllability and stability. Its high strength and toughness ensure that the micro-weight does not deform or break during complex operations. Low thermal expansion characteristics ensure the dimensional stability of the device at body temperature or in surgical environments. The corrosion resistance and biocompatibility of the alloy enable it to resist erosion by body fluids and meet the requirements of long-term implantation or multiple uses. Non-toxic properties ensure that it meets medical safety standards.

Processing and quality requirements : Micro-weights are prepared by powder metallurgy or metal injection molding (MIM), combined with hot isostatic pressing to ensure high density and defect-free structure. Ultra-precision machining (such as laser micromachining or electrospark machining) is used to manufacture micron-level components, with tolerances controlled within ± 0.005 mm and surfaces polished to a mirror effect ($Ra < 0.1 \mu\text{m}$). Heat treatment optimizes mechanical properties, and surface treatment (such as electroless nickel plating or DLC coating) enhances biocompatibility and corrosion resistance. Quality control needs to verify composition, density and microstructure to ensure the reliability and safety of the device in interventional treatment.

Technical challenges and optimization : The processing of micro-weights is difficult, and advanced equipment and processes are required to ensure accuracy and cost control. The microstructure needs to be strictly controlled to avoid pores or inclusions that affect performance. In the future, 3D printing technology can realize the customized production of micro-weights to meet personalized medical needs while improving production efficiency.

5.4 Application of Tungsten-Nickel-Iron Alloy in Precision Instruments

Tungsten -nickel-iron alloy plays an important role in the field of precision instruments due to its high density, excellent mechanical properties, good corrosion resistance and low thermal expansion characteristics. Precision instruments have extremely strict requirements on materials and need to provide high quality, high stability and high precision performance in a limited space. Tungsten -nickel-iron alloy can meet these requirements and is widely used in scenarios that require precise balance, vibration suppression or high stability. Its high density and mechanical strength make it an ideal material for precision instrument counterweights and key components. The following will discuss its application in precision instrument counterweights and lithography machine platform balance blocks in detail.

5.4.1 Precision instrument counterweights

Tungsten -nickel-iron alloy is widely used as a counterweight material in precision instruments to optimize the center of gravity distribution of the equipment and improve motion accuracy and stability. Precision instruments such as optical measuring equipment, lasers, scientific experimental devices and

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high-end testing instruments usually require accurate mass balance in a compact space to reduce vibration, improve positioning accuracy or ensure long-term operational stability. The high density and mechanical properties of tungsten -nickel-iron alloy enable it to meet these demanding requirements.

Application scenarios : In optical measuring equipment, such as high-precision laser interferometers or microscopes, tungsten-nickel-iron alloy counterweights are used to adjust the center of gravity of the equipment to ensure the stability of the optical system when moving or scanning. In scientific experimental devices, such as gravitational wave detectors or high-precision balances, alloy counterweights are used to suppress external vibration interference and improve measurement sensitivity. In high-end testing instruments, such as semiconductor testing equipment, counterweights are used to optimize the balance of robotic arms or platforms and reduce motion errors.

Performance advantages : The high density of the alloy can provide sufficient mass in a small volume, which is suitable for the compact design requirements of precision instruments. Its low thermal expansion characteristics ensure that the counterweight remains dimensionally stable under temperature changes (such as laboratory temperature differences or equipment operation heat), avoiding deformation caused by thermal stress. The excellent strength and toughness enable the counterweight to withstand vibration or impact during instrument operation to prevent deformation or fatigue failure. The corrosion resistance of the alloy enables it to resist erosion by chemicals or moisture in the laboratory environment, extending its service life. In addition, the weak ferromagnetism of the alloy has been optimized so that it will not interfere with the electromagnetic system of precision instruments, making it suitable for high-sensitivity applications.

Processing and quality requirements : Precision instrument weights are usually produced by powder metallurgy (liquid phase sintering) combined with hot isostatic pressing to ensure high density and microstructural uniformity. Precision machining (such as five-axis CNC or EDM) is used to produce complex shapes with tolerances controlled in the micron range, and the surface needs to be polished to a high finish to reduce friction and wear. Heat treatment can eliminate processing stresses and improve toughness. Surface treatment (such as electroless nickel plating) enhances corrosion resistance and aesthetics. Quality control needs to verify density uniformity, mechanical properties and defect-free structure to ensure the stability of the weight in dynamic operation.

5.4.2 Lithography Platform Balance Block

Tungsten -nickel-iron alloy is used as a platform balance block in photolithography machines to ensure the stability and positioning accuracy of the equipment during high-precision semiconductor manufacturing. Photolithography machines are core equipment in semiconductor production, used to engrave micro-nanoscale circuit patterns on silicon wafers, and have extremely high requirements for vibration suppression, mass distribution and thermal stability.

The high density and low thermal expansion characteristics of tungsten -nickel-iron alloy make it an ideal material for platform balance blocks , which can effectively improve the performance and reliability of

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photolithography machines.

Application scenarios : In extreme ultraviolet (EUV) or deep ultraviolet (DUV) lithography machines, tungsten-nickel-iron alloy balance weights are used on the workbench or optical platform of the lithography machine to optimize mass distribution, reduce vibration and tilt, and ensure that the positioning accuracy of silicon wafers reaches the sub-nanometer level. In wafer handling systems, alloy balance weights are used as counterweights for robotic arms or transfer platforms to maintain dynamic balance and improve production efficiency. Balance weights are also used to suppress micro-vibrations during the operation of lithography machines and protect optical systems from interference.

Performance advantages : The high density of the alloy can provide efficient mass distribution in a limited space, optimize the dynamic balance of the lithography platform, and reduce the impact of mechanical vibration on pattern accuracy. Its low thermal expansion characteristics ensure that the balance block remains dimensional stable under the heat generated by the operation of the lithography machine or the ambient temperature difference, avoiding minor deformation caused by thermal stress. High strength and toughness enable the balance block to withstand high-frequency vibration and mechanical stress to prevent fatigue failure. The corrosion resistance of the alloy enables it to resist erosion by chemicals (such as cleaning agents) in the clean room environment of the lithography machine, making it suitable for long-term use. In addition, the alloy is optimized to have low magnetism and will not interfere with the electromagnetic or optical systems of the lithography machine.

Processing and quality requirements : The balancing weights are manufactured by powder metallurgy combined with hot isostatic pressing to ensure high density and non-porous structure. Ultra-precision machining (such as laser micromachining or five-axis CNC) is used to manufacture complex shapes, with tolerances controlled at the submicron level and extremely high surface finish requirements to reduce vibration and friction. Heat treatment optimizes mechanical properties, and surface coatings (such as DLC or TiN) enhance wear and corrosion resistance. Quality control requires verification of density consistency, microstructural uniformity and mechanical properties, and metallographic analysis and vibration testing to ensure the stability of the balancing weights in high-frequency operations.

Technical challenges and optimization : The balancing block of the lithography machine has extremely high requirements for processing accuracy, and advanced equipment and processes are needed to ensure sub-micron tolerances, which increases production costs. The microstructure must be defect-free to avoid vibration amplification, and the sintering and heat treatment parameters must be strictly controlled. The magnetism of the alloy needs to be further optimized to meet the extremely low tolerance of the lithography machine to electromagnetic interference, which can be solved by adjusting the formula or using non-magnetic surface treatment.

5.4.3 High-speed machine tool spindle damping block

Tungsten -nickel-iron alloy is widely used as a high-speed machine tool spindle damping block in the field of precision instruments due to its high density, excellent mechanical properties and good vibration

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attenuation characteristics. High-speed machine tools (such as CNC machine tools, grinders or lathes) will produce significant vibration and dynamic stress when running at high speeds, which may lead to reduced machining accuracy or increased tool wear. Spindle damping blocks effectively suppress vibrations and improve the machining stability and surface quality of machine tools by increasing mass and optimizing the damping effect. The high density and mechanical properties of tungsten -nickel-iron alloy make it an ideal material for damping blocks, which can ensure the performance of machine tools in high-speed and high-stress environments.

Application scenarios : Tungsten -nickel-iron alloy spindle damping blocks are used in the spindle system of high-speed CNC machine tools, especially in the field of precision machining, such as aerospace parts, automotive engine components or semiconductor equipment manufacturing. The damping block is installed on the spindle or its supporting structure to reduce the swing or resonance of the spindle when it rotates at high speeds (such as tens of thousands of revolutions per minute) by adjusting the mass distribution and absorbing vibration energy. This damping block is also used in ultra-precision lathes or grinders to ensure high finish and dimensional accuracy of the machined surface.

Performance advantages : The high density of the alloy allows sufficient mass to be provided in a limited space, optimizing the dynamic balance of the spindle and significantly reducing the vibration amplitude. Its high strength and toughness ensure that the damping block does not deform or fatigue fracture under high-speed rotation and periodic stress, and can withstand the dynamic load of machine tool operation for a long time. The low thermal expansion characteristics enable the damping block to maintain dimensional stability under the heat generated by friction or motor during processing, avoiding thermal deformation that affects the spindle accuracy. The corrosion resistance of the alloy enables it to resist chemical erosion by machine tool coolants or lubricants, making it suitable for long-term use. In addition, the weak ferromagnetism of the alloy has been optimized so that it will not interfere with the electromagnetic control system of the machine tool, making it suitable for high-precision electronic equipment.

Processing and quality requirements : Spindle damping blocks are manufactured by powder metallurgy (liquid phase sintering) combined with hot isostatic pressing to ensure high density and microstructural uniformity to provide excellent damping performance. Precision machining (such as five-axis CNC or EDM) is used to manufacture complex shapes with tolerances controlled in the micron range and surfaces polished to a high finish to reduce friction and vibration amplification. Heat treatment (such as annealing) eliminates processing stresses and improves toughness. Surface treatments (such as electroless nickel plating or DLC coating) enhance corrosion and wear resistance. Quality control requires verification of density consistency, mechanical properties and defect-free structure, and vibration testing and metallographic analysis to ensure the stability of the damping block under high-frequency vibration.

Technical challenges and optimization : High density and high hardness increase the difficulty of processing, and high-precision equipment and optimized cutting parameters are required to control costs. The microstructure needs to be strictly controlled to avoid pores or inclusions that affect the damping

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effect. The magnetism of the alloy needs to be further optimized to avoid interfering with the precision sensors of the machine tool, which can be solved by reducing the iron content or using non-magnetic coatings.

5.4.4 Precision optical platform vibration reduction components

Tungsten -nickel-iron alloy is used as a vibration reduction component in precision optical platforms to suppress external or internal vibrations and ensure high precision and stability of optical systems. Precision optical platforms are widely used in lasers, optical measurement equipment, microscopes, semiconductor lithography machines and other fields, and have extremely high requirements for vibration control, because small vibrations may cause optical component misalignment or measurement errors. The high density and excellent mechanical properties of tungsten -nickel-iron alloy enable it to effectively absorb and attenuate vibrations, making it a preferred material for vibration reduction components.

Application scenarios : In precision optical platforms, tungsten-nickel-iron alloy vibration damping components are used to support structures or isolation systems to absorb vibrations from the ground, equipment operation or the external environment. For example, in laser interferometers or high-resolution microscopes, alloy vibration damping blocks are used for platform bases or support frames to stabilize the position of optical components. In semiconductor lithography machines, vibration damping components are used to isolate platforms to prevent vibrations from interfering with the characterization of sub-nanometer patterns. Vibration damping components can also be used in the support system of astronomical telescopes to ensure the stability of the mirror in a micro-vibration environment.

Performance advantages : The high density of the alloy can provide sufficient mass, enhance the inertia of the platform, and reduce the amplitude of vibration transmission. Its high strength and toughness ensure that the vibration reduction components will not deform or fatigue under long-term vibration or dynamic loads, maintaining the structural integrity of the platform. The low thermal expansion characteristics enable the components to maintain dimensional stability under laboratory temperature differences or equipment operation heat, avoiding small displacements caused by thermal stress. The corrosion resistance of the alloy enables it to resist erosion by chemicals or moisture in the laboratory environment, suitable for long-term use. The optimized weak ferromagnetism will not interfere with the electromagnetic system or high-sensitivity sensors of the optical platform, meeting high-precision requirements.

Processing and quality requirements : Vibration damping components are manufactured by powder metallurgy combined with hot isostatic pressing to ensure high density and uniform microstructure to optimize vibration attenuation performance. Ultra-precision machining (such as laser micromachining or five-axis CNC) is used to manufacture complex shapes with sub-micron tolerances and mirror-polished surfaces to reduce vibration amplification. Heat treatment optimizes mechanical properties, and surface coatings (such as TiN or DLC) enhance wear and corrosion resistance. Quality control requires verification of density uniformity, mechanical properties and non-porous structure, and vibration testing

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and spectrum analysis to ensure the vibration damping effect of the components.

Technical challenges and optimization : The machining precision of the vibration reduction components is extremely high, and advanced equipment is needed to ensure sub-micron tolerances, which increases production costs. The microstructure needs to be defect-free to avoid vibration amplification, and the sintering and heat treatment parameters need to be strictly controlled. The magnetic properties of the alloy need to be optimized to meet the low tolerance of the optical platform to electromagnetic interference, which can be solved by adjusting the formula or using non-magnetic surface treatment.

5.5 Other Applications of Tungsten Nickel Iron Alloy

Tungsten -nickel-iron alloy, with its high density, excellent mechanical properties, corrosion resistance and thermal stability, is not only widely used in aerospace, military, medical and precision instrument fields, but also shows unique potential in emerging technologies. Thanks to its high density and mechanical properties, tungsten-nickel-iron alloy has gradually attracted attention in the fields of 3D printing technology and energy. These fields have high requirements for material performance, and tungsten-nickel-iron alloy can provide reliable solutions to meet the needs of complex manufacturing and extreme environments. The following will discuss in detail its application potential in the fields of 3D printing technology and energy.

5.5.1 Application of 3D printing technology

The application of tungsten -nickel-iron alloy in 3D printing technology (additive manufacturing) has gradually become a hot topic in research and industry. 3D printing technology directly manufactures parts of complex shapes by stacking materials layer by layer, providing flexibility for the rapid prototyping of high-performance components. The high density and mechanical properties of tungsten -nickel-iron alloy give it significant advantages in 3D printed parts that require high strength, wear resistance and complex geometry, especially for small batch and customized production scenarios.

Application scenarios : Tungsten -nickel-iron alloys are used to manufacture complex-shaped parts such as aerospace counterweights, medical shielding parts, and precision instrument damping blocks through selective laser melting (SLM) or electron beam melting (EBM) technology. In the industrial field, the alloy can be used to print high- wear-resistant molds or tool parts, such as inserts for injection molds or reinforced parts for cutting tools. In the field of scientific research, 3D printed tungsten -nickel-iron alloys are used to manufacture customized parts for experimental devices, such as high-density counterweights or radiation-resistant shielding parts.

Performance advantages: The high density of the alloy can meet the needs of 3D printed parts to achieve high-quality distribution in a limited space. This feature is particularly prominent in the field of precision weight distribution. For example, in the gyroscope components of aerospace equipment, it is necessary to achieve accurate weight ratios in a very small installation space to ensure the balanced

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operation of the equipment. The alloy can perfectly adapt to this stringent requirement with its high density; in the shielding application of the nuclear industry, high density can effectively block radiation penetration and provide reliable protection for equipment and personnel. Even complex special-shaped shielding parts can still maintain a uniform high-density distribution after being formed by 3D printing technology to ensure the stability of the shielding effect. Its combination of high strength and toughness is to ensure the reliability of printed parts. In the precision transmission parts of automobile engines, the parts need to withstand dynamic loads and complex mechanical stresses for a long time. The parts made of this alloy can not only withstand high- frequency force impacts, but also maintain structural integrity under extreme working conditions, preventing equipment failures caused by deformation or fracture from the root, and greatly reducing maintenance costs. The low thermal expansion characteristics allow the parts to maintain dimensional stability during the printing process and the subsequent temperature changes in the use environment. When printing sensor brackets in high-temperature industrial furnaces, the temperature fluctuates dramatically from the high-temperature molten state during printing to the continuous high-temperature environment during use, and then to the cooling process after shutdown. The low thermal expansion performance of the alloy can avoid dimensional deviations of components due to thermal expansion and contraction, ensure the precise coordination of sensors and other components, and maintain the accuracy of detection data .

Processing and quality requirements : 3D printing of tungsten -nickel-iron alloys requires the use of high-purity mixed powders (tungsten, nickel, iron) or pre-alloyed powders, which are melted layer by layer under high energy input by SLM or EBM. The printing process needs to optimize laser power, scanning speed and layer thickness to ensure high density and no pores. After printing, hot isostatic pressing (HIP) is usually combined to eliminate tiny pores and improve mechanical properties. Precision post-processing (such as CNC machining or polishing) is used to achieve high precision and surface finish. Quality control needs to verify composition consistency, density uniformity and microstructure, and ensure that the printed parts meet aerospace or medical standards through XRF, SEM-EDS and tensile testing.

Technical challenges and optimization : The high melting point and thermal conductivity of tungsten lead to large thermal gradients during printing, which are prone to cracks or residual stress. Printing parameters (such as energy density) need to be optimized to improve quality. The powder cost is high, and the cost needs to be reduced by recycling or improving the powder making process. The weak ferromagnetism of the alloy needs to be controlled to avoid interfering with high-precision equipment, which can be solved by adjusting the formula or surface treatment.

5.5.2 Potential in the energy sector

Tungsten -nickel-iron alloys have shown significant application potential in the energy sector, especially in scenarios that require high-density, high-temperature-resistant and corrosion-resistant materials, such as nuclear energy, renewable energy and energy storage equipment. Extreme environments in the energy sector (such as high temperature, high radiation or corrosive atmosphere) place stringent demands on material performance, and the unique properties of tungsten-nickel-iron alloys enable them to meet these

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requirements and provide support for the efficiency and reliability of energy equipment.

Application scenarios : In the field of nuclear energy, tungsten-nickel-iron alloys are used for radiation shielding components or control rod counterweights of nuclear reactors to absorb neutrons and gamma rays and protect equipment and personnel. In the field of renewable energy, the alloys are used for blade counterweights of wind turbines to optimize rotational balance and improve power generation efficiency. In energy storage devices, the alloys can be used as counterweights for battery testing equipment or energy conversion devices to stabilize system operation. In addition, the alloys can also be used to manufacture corrosion-resistant components for high-temperature fuel cells or geothermal equipment.

Performance advantages : The high density of the alloy and the high atomic number of tungsten enable it to effectively shield radiation, suitable for shielding applications in the nuclear energy field. Its high strength and toughness ensure that the components remain structurally stable under high temperature or mechanical stress, suitable for the dynamic environment in energy equipment. The low thermal expansion characteristics enable the alloy to maintain dimensional stability in high-temperature cycles (such as nuclear reactors or fuel cell operations) and avoid deformation caused by thermal stress. The corrosion resistance of the alloy enables it to resist erosion by chemicals in energy equipment (such as acidic electrolytes or high-temperature steam), extending its service life. The optimized weak ferromagnetism will not interfere with the electromagnetic system of energy equipment, suitable for high-precision control scenarios.

Processing and quality requirements : Energy sector components are manufactured by powder metallurgy (liquid phase sintering) combined with hot isostatic pressing to ensure high density and microstructural homogeneity. Precision machining (such as EDM or laser cutting) is used to produce complex shapes with tolerances in the micrometer range, and the surface needs to be polished or coated to enhance corrosion and wear resistance. Heat treatment optimizes mechanical properties, and surface coatings (such as CVD WC or PVD TiN) improve high temperature resistance and corrosion resistance. Quality control requires verification of density, composition and radiation resistance, and component reliability is ensured by metallographic analysis, tensile testing and radiation attenuation testing.

Technical challenges and optimization : In high temperature environments, the alloy needs to further improve oxidation resistance and thermal stability, which can be achieved by optimizing the nickel-iron ratio or adding high-temperature resistant coatings. The cost of processing complex parts is high, and the manufacturing process (such as additive manufacturing) needs to be improved to improve efficiency. Nuclear energy applications require strict control of trace impurities (such as oxygen or carbon) to avoid radiation-induced performance degradation.

5.5.3 Golf club weights

Tungsten -nickel-iron alloy plays an important role in the field of golf club weights due to its high density, excellent mechanical properties and corrosion resistance . For golf clubs, accurate mass distribution is the core element to optimize swing balance, improve shot accuracy and control, and tungsten-nickel-iron

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alloy can perfectly meet this demand .

Its high-density characteristics show significant advantages in the supply of mass within a limited space. The golf club head has a delicate structure, and the space inside that can be used to install the counterweight is very limited. Traditional materials often require a large volume to achieve the required mass, which can easily destroy the overall design and aerodynamic performance of the club head. Tungsten-nickel-iron alloy, with its ultra-high density, can provide sufficient mass in a small volume, allowing designers to flexibly adjust the installation position of the counterweight and accurately optimize the center of gravity distribution of the club. For example, adding a small piece of tungsten - nickel-iron alloy counterweight to the rear of the driver's head can effectively move the center of gravity backward, increase the tolerance when hitting the ball, and help athletes to hit a more ideal ball path even if the swing is not perfect; installing the counterweight at the bottom of the club head can lower the center of gravity, increase the trajectory height of the shot, and let the ball fly farther. This ability to flexibly adjust the center of gravity allows athletes of different levels to find the most suitable balance point according to their own swing characteristics, thereby enhancing the stability and accuracy of the shot .

Not only that, the excellent mechanical properties and durability of tungsten-nickel-iron alloy provide a solid guarantee for the stable operation of the counterweight in complex environments. Golf is mostly played outdoors, and the club will frequently experience violent impacts during the swing, accidental collisions with the ground, and the test of different climatic conditions. At the moment of the swing, the counterweight needs to withstand huge centrifugal force and torque. If the material strength is insufficient, it is very easy to deform, crack, or even fall off, which directly affects the performance and service life of the club. Tungsten-nickel-iron alloy has high strength and good toughness, which can easily withstand these dynamic loads and mechanical stresses and maintain structural integrity for a long time. Even in rainy days, wet grass and other environments, its excellent corrosion resistance can still play a role, effectively resisting the erosion of corrosive components in water vapor and soil, avoiding rust and surface peeling of the counterweight, and ensuring its quality and performance for a long time .

For professional players who pursue the ultimate performance and high-end golf equipment, tungsten-nickel-iron alloy weights are an indispensable choice. Professional players are extremely sensitive to subtle changes in their swings, and even slight deviations in the quality of the weights may affect their performance. The high density of tungsten-nickel-iron alloys allows weight adjustments to be accurate to grams or even milligrams, meeting the precision requirements of professional levels. At the same time, its stable performance can also ensure that the clubs always maintain consistent performance during long-term, high-intensity training and competitions, helping athletes to stabilize their performance and achieve better results on the field.

Application scenarios : Tungsten -nickel-iron alloy weights are widely used in golf club heads (such as irons, woods or putters), especially in high-end custom clubs. Weights are usually embedded in the bottom or back of the club head to adjust the center of gravity position and optimize the club's moment of inertia (MOI), thereby improving the stability and tolerance of the shot. In irons, weights help achieve a low center of gravity design, increase the ball's launch angle and rotation control; in putters, weights

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are used to enhance the stability of the swing and improve the accuracy of the putt. The alloy can also be used to weight the shaft of the club to optimize the overall sense of balance.

Performance advantages : The high density of the alloy allows for efficient mass distribution in a small volume, which allows for more precise adjustment of the club's center of gravity compared to traditional materials such as steel or lead, reducing the club head volume while improving performance. Its high strength and toughness ensure that the weight does not deform or break during high-frequency swings or accidental impacts, extending the life of the club. The low thermal expansion characteristics allow the weight to remain dimensionally stable under outdoor temperature changes (such as high temperatures in summer or low temperatures in winter), avoiding affecting the performance of the club. The corrosion resistance of the alloy enables it to resist erosion by grass moisture, rain or detergents, making it suitable for long-term outdoor use. In addition, the alloy is non-toxic and environmentally friendly, meeting the environmental protection requirements of golf equipment.

Processing and quality requirements : Counterweights are manufactured by powder metallurgy combined with hot isostatic pressing to ensure high density and microstructural uniformity to provide stable mass distribution. Precision machining (such as CNC turning or milling) is used to manufacture complex shapes with tolerances controlled in the micron range, and the surface needs to be polished to a high finish to enhance aesthetics and embedding accuracy. Heat treatment (such as annealing) can eliminate processing stresses and improve toughness. Surface treatment (such as Ni-P electroplating) enhances corrosion resistance and appearance. Quality control requires verification of density consistency, mechanical properties and defect-free structure, and metallographic analysis to ensure the uniformity and reliability of counterweights.

Technical challenges and optimization : High density and high hardness increase the difficulty of processing, and high-precision equipment and optimized cutting parameters are required to reduce costs. The microstructure needs to be strictly controlled to avoid pores or inclusions that affect the mass distribution. The shape and position of the counterweight block need to be precisely designed to match different club types, and the center of gravity distribution can be optimized through computer simulation. In the future, additive manufacturing technology (such as SLM) can realize customized counterweight block production to meet personalized needs and improve production efficiency.

5.5.4 Racing engine balancing kit

Tungsten -nickel-iron alloys are used as balancing components in racing engines to optimize the dynamic balance of the crankshaft or flywheel, reduce vibration and improve engine performance and durability. Racing engines (such as F1 cars or Le Mans endurance race vehicles) need to operate at high speeds (up to tens of thousands of revolutions per minute) and extreme conditions, and have extremely high requirements for vibration control and mass distribution.

The high density and mechanical properties of tungsten -nickel-iron alloys make them ideal materials for balancing components, which can maintain structural stability during intense movement, effectively

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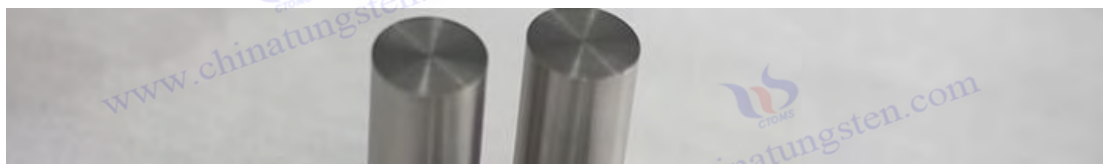
suppress vibration, improve power output and extend engine life.

Application scenarios : Tungsten -nickel-iron alloy balancing components are used in the crankshaft, flywheel or piston system of racing engines to optimize the mass distribution of rotating parts and reduce unbalanced vibration at high speeds. In F1 racing engines, alloy balance blocks are embedded in the crankshaft or flywheel to correct the rotational inertia and ensure smooth operation. In endurance racing vehicles, balancing components are used to improve the long-term stability of the engine and reduce fatigue damage to other components (such as the transmission system) caused by vibration. The alloy can also be used in the counterweight components of turbochargers to optimize the dynamic balance of turbine blades.

Performance advantages : The high density of the alloy can provide sufficient mass in a small volume, accurately adjust the balance of the crankshaft or flywheel, significantly reduce the vibration amplitude at high speed, reduce energy loss and increase power output. Its high strength and toughness ensure that the balance components will not deform or break under high-frequency rotation and mechanical stress, which is suitable for the extreme working conditions of racing engines. The low thermal expansion characteristics enable the components to maintain dimensional stability in the high temperature environment of the engine (such as high-temperature combustion chambers), avoiding imbalance caused by thermal stress. The corrosion resistance of the alloy enables it to resist chemical erosion by fuel, lubricating oil or high-temperature exhaust gas, extending its service life.

Processing and quality requirements : Balanced components are manufactured by powder metallurgy combined with hot isostatic pressing to ensure high density and uniform microstructure to provide excellent dynamic balancing performance. Ultra-precision machining (such as five-axis CNC or laser cutting) is used to manufacture complex shapes with sub-micron tolerances and mirror-polished surfaces to reduce friction and vibration amplification. Heat treatment optimizes mechanical properties, and surface coatings (such as DLC or TiN) enhance wear and corrosion resistance. Quality control requires verification of density consistency, mechanical properties and non-porous structure, and vibration testing and spectrum analysis to ensure component stability at high speeds.

Technical challenges and optimization : The cost of machining high-precision balancing components is high, and the process needs to be optimized to improve efficiency. The microstructure needs to be defect-free to avoid vibration amplification, and the sintering and heat treatment parameters need to be strictly controlled. The magnetic properties of the alloy need to be optimized to meet the engine's low tolerance for electromagnetic interference, which can be solved by adjusting the formula or using non-magnetic surface treatment.



CTIA GROUP LTD Tungsten Nickel Iron Alloy

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Chapter 6 Advantages and Disadvantages of Tungsten Nickel Iron Alloy

6.1 Analysis of the advantages of tungsten nickel iron alloy

Tungsten -nickel-iron alloy has shown a wide range of application value in aerospace, military, medical, precision instruments and other fields. The alloy combines the high density and high melting point characteristics of tungsten with the toughness and corrosion resistance provided by nickel and iron , giving it significant advantages in a variety of high-performance scenarios. In particular, its high density and strength, as well as good processing properties, make it an ideal material for many key components. The following will analyze in detail the advantages of tungsten -nickel-iron alloy in terms of high density, strength and processing properties.

6.1.1 High density and strength

Tungsten -nickel-iron alloy has become the material of choice for many demanding applications due to its high density and excellent mechanical properties. The high atomic number and density of tungsten, combined with the reinforcement of nickel and iron, make the alloy perform well in scenarios requiring high mass distribution, high strength and durability, especially suitable for aerospace counterweights, military armor-piercing cores and medical shielding parts.

Advantages : The high density of the alloy can provide significant mass in a small volume, which is superior to traditional materials such as lead or steel. For example, in the aerospace field, counterweights need to achieve precise center of gravity adjustment in a limited space. The high density of tungsten-nickel-iron alloy makes the component smaller, reduces the overall weight of the equipment, and improves design flexibility. In the military field, the high density of the alloy gives the armor-piercing core extremely high kinetic energy penetration, which can effectively fight armored targets. Its high strength ensures that the alloy maintains structural integrity in high-stress environments, such as high-speed rotating engine parts or impact loads. The alloy can withstand vibration and mechanical stress without breaking or deformation. Moderate toughness makes the alloy less brittle when impacted, enhances the fatigue resistance of the components, and is suitable for harsh environments for long-term use. In addition, the low thermal expansion characteristics of the alloy ensure that it remains dimensional stable under temperature changes and avoids deformation caused by thermal stress, which is particularly important in high or low temperature environments.

Application value : The combination of high density and strength makes tungsten-nickel-iron alloy irreplaceable in a variety of scenarios. In aerospace counterweights, the alloy optimizes the balance and stability of aircraft; in medical radiation shielding, its high density efficiently absorbs X-rays and gamma rays; in military armor-piercing cores, the strength and density of the alloy ensure high penetration and reliability. These characteristics enable the alloy to meet the high material requirements of high-performance applications.

Technical support : High density and strength are achieved through powder metallurgy and liquid phase

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sintering. By precisely controlling the ratio of tungsten, nickel and iron and sintering conditions, the alloy can achieve high density and uniform microstructure. Hot isostatic pressing further eliminates porosity and improves strength and toughness. Quality control is verified by tensile testing, metallographic analysis and other methods to ensure that the alloy performance meets aerospace or military standards.

6.1.2 Processing performance

Tungsten -nickel-iron alloy is another important advantage. Although tungsten itself has high hardness and is difficult to process, the addition of nickel and iron significantly improves the machinability of the alloy, enabling it to be made into parts of complex shapes through a variety of processes. Compared with pure tungsten, tungsten-nickel-iron alloy shows better adaptability in machining, forming and surface treatment, meeting the needs of precision manufacturing.

Advantages : Nickel and iron act as binder phases, which reduce the overall hardness of the alloy and enable it to be formed by conventional machining processes such as turning, milling, drilling and grinding. The moderate toughness of the alloy reduces the risk of cracking during processing and is suitable for manufacturing high-precision parts, such as collimators for medical devices or counterweights for precision instruments. The liquid phase sintering process gives the alloy a high density and uniform microstructure after sintering, which facilitates subsequent processing to achieve micron-level tolerances. The alloy also supports electrospark machining (EDM) and laser cutting, suitable for the manufacture of complex geometries, such as lithography machine balance blocks or surgical robot counterweights. In addition, the alloy has excellent surface treatment performance, and can be polished, electroless nickel plating or PVD coating to improve corrosion resistance and aesthetics, meeting the stringent requirements of the medical and precision instrument fields. Heat treatment (such as annealing) can further optimize processing performance, eliminate internal stress, improve toughness, and make the alloy easier to finish.

Application value : Good processing performance enables tungsten -nickel-iron alloy to meet diverse manufacturing needs. In the medical field, the alloy can be processed into shields or collimators with complex shapes, high precision and smooth surface; in the aerospace field, the alloy can be made into high-precision counterweights to optimize aircraft performance; in precision instruments, the alloy can be processed into micro damping blocks or balance components to meet sub-micron precision requirements. These characteristics make the alloy widely applicable in high-tech fields.

Technical support : Improved processing performance relies on optimization of powder metallurgy processes, such as precise control of sintering temperature and atmosphere to reduce porosity and inclusions. Hot isostatic pressing and heat treatment processes further improve the machinability of the alloy. Advanced processing equipment ensures high precision and surface quality.

6.2 Limitations of Tungsten Nickel Iron Alloy

Although tungsten -nickel-iron alloys are widely used in aerospace, military, medical and precision

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instrument fields due to their high density, excellent mechanical properties and corrosion resistance, they also have some limitations that restrict their use in certain scenarios. Cost and resource limitations as well as environmental and health impacts are the two main limitations of tungsten-nickel-iron alloys, which affect the sustainability of their production, processing and widespread application. The following will analyze these limitations and their impact on applications in detail.

6.2.1 Cost and resource constraints

tungsten -nickel-iron alloy are high, and are limited by the scarcity of raw materials, which to some extent restricts its widespread application in certain fields. As a rare metal, the mining, refining and processing of tungsten are complex and energy-intensive, resulting in the overall cost of tungsten -nickel-iron alloy being higher than traditional materials such as steel or aluminum, which poses a challenge to cost-sensitive application scenarios.

Limitations : The scarcity of tungsten resources is the main cost driver. Tungsten ore reserves are limited worldwide and are mainly concentrated in a few countries. Unstable supply chains may lead to price fluctuations. High-purity refining of tungsten requires multiple chemical and metallurgical processes, which increases the cost of raw materials. Although nickel and iron are more common, high purity requirements (especially for medical and aerospace applications) further increase material costs. During the production process, powder metallurgy (liquid phase sintering) and hot isostatic pressing (HIP) require high-temperature and high-pressure equipment, which consumes a lot of energy and has high equipment maintenance costs. Precision machining (such as five-axis CNC or EDM) requires high-wear-resistant tools (such as CBN or diamond tools) due to the high hardness of the alloy, which has low processing efficiency and fast tool wear, resulting in increased processing costs. In addition, although emerging technologies such as 3D printing have improved design flexibility, the high cost of special alloy powders and equipment limits large-scale applications. Strict quality control requirements (such as XRF, SEM-EDS analysis) further increase production costs. These factors make tungsten-nickel-iron alloys less competitive in cost-sensitive areas (such as consumer products or low-end industrial applications).

Application impact : High cost limits the use of tungsten-nickel-iron alloys in low-budget projects. For example, in some civilian fields (such as general machinery manufacturing), cheaper materials such as lead or steel may be preferred, although the performance is not as good as the alloy. In the aerospace and military fields, although high performance requirements are prioritized, cost control is still an important consideration in project planning. Resource limitations may also lead to supply chain risks, especially when international trade is restricted or geopolitical tensions occur, affecting the stable supply of alloys.

Improvement direction : To reduce costs, the tungsten ore refining process can be optimized to improve resource utilization, such as using more efficient beneficiation technology or recycling scrap alloys. Improving powder preparation and sintering processes (such as low-temperature sintering) can reduce energy consumption. Developing more efficient processing technologies (such as additive manufacturing optimization) or alternative tool materials can reduce processing costs. Supply chain diversification (such as developing new mineral sources or international cooperation) can help ease

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resource constraints and ensure a stable supply of raw materials.

6.2.2 Environmental and health impacts

There are certain environmental and health impacts in the production and use of tungsten -nickel-iron alloys. Although it is non-toxic and better than traditional materials such as lead, potential risks still need to be paid attention to in some links. The mining, processing and waste disposal of tungsten, nickel and iron may have an impact on the environment, and the potential health risks of nickel also need to be strictly managed to ensure the safety of the alloy in the medical and civilian fields.

Limitations : Tungsten mining and refining processes have a significant impact on the environment, including land destruction, water pollution and energy consumption. Chemical reagents (such as flotation agents) are often used in tungsten beneficiation, which may produce wastewater and tailings. If not handled properly, they will pollute soil and water sources. Powder metallurgy and hot isostatic pressing processes require high temperature and high pressure, consume a lot of energy, produce carbon emissions, and increase the environmental burden. Cutting fluids and polishing wastes in the processing process may release harmful substances if not properly handled. Nickel, as one of the alloy components, has potential sensitization and toxicity risks. Especially in the medical field, long-term contact or implantation may cause skin allergies or tissue reactions, although tungsten -nickel-iron alloys have good overall biocompatibility. In addition, the weak ferromagnetism of the alloy may cause slight interference in highly sensitive electromagnetic environments (such as MRI equipment), which needs to be solved by formula optimization or surface treatment. The recycling and treatment of waste alloys requires special processes, and improper disposal may lead to resource waste or environmental pollution.

Application impact : Environmental impact increases the difficulty of alloy application in industries with strict environmental requirements (such as medical or green energy). High energy consumption and waste disposal costs in the production process may push up overall expenses and affect market competitiveness. Nickel's potential health risks require strict biocompatibility testing in medical applications (such as implants or surgical tools), increasing development cycles and costs. In highly sensitive precision instruments, the magnetism of the alloy needs to be specially controlled, which may limit its use in certain scenarios with high electromagnetic compatibility requirements. Imperfect waste management may cause regulatory issues, especially in areas with strict environmental regulations.

Improvement direction : To reduce environmental impact, green mineral processing technology (such as non-toxic flotation agents) and closed-loop water treatment systems can be used to reduce pollution. Optimizing sintering and heat treatment processes (such as using renewable energy) can reduce carbon emissions. Developing efficient recycling technology to promote the recycling of scrap alloys can reduce resource waste and environmental burden. In terms of health, the potential allergic risk can be reduced by reducing the nickel content or using biocompatible coatings (such as DLC or TiN) to ensure the safety of medical applications. For magnetic issues, the alloy formula can be optimized (such as reducing the iron content) or non-magnetic surface treatment technology can be developed to meet the needs of highly sensitive equipment. In the future, green manufacturing technology and strict environmental protection

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standards will further promote the sustainable development of tungsten -nickel-iron alloys.

6.3 Comparison between WNiFe alloy and other materials

Tungsten -nickel-iron alloy is widely used in aerospace, military, medical and precision instruments due to its high density, excellent mechanical properties and corrosion resistance. However, compared with other high-density materials, tungsten-nickel-iron alloy has its own advantages and disadvantages in terms of performance, processability and cost . In order to fully evaluate its applicability, it is necessary to compare it with tungsten-nickel-copper alloy, lead-based alloy and other high-density materials to analyze their respective characteristics and application scenarios. The following will discuss in detail the comparison between tungsten -nickel-iron alloy and these materials.

6.3.1 Comparison with tungsten-nickel-copper alloy

Tungsten -nickel-copper alloy is another high-density alloy similar to tungsten-nickel-iron alloy, which is often used in similar application scenarios, such as aerospace counterweights, medical shielding parts and precision instrument components. Both use tungsten as the main component, supplemented by nickel and copper (or iron) as the bonding phase, but due to the difference in the properties of copper and iron, tungsten-nickel-copper alloy has significant differences from tungsten-nickel-iron alloy in some properties.

Performance comparison : The density of tungsten -nickel-iron alloy ($16.5\text{-}18.75\text{ g/cm}^3$) is comparable to that of tungsten-nickel-copper alloy ($16.5\text{-}18.5\text{ g/cm}^3$), and both are suitable for high-density counterweight and shielding applications. Tungsten -nickel-iron alloy has excellent mechanical properties, high tensile strength ($800\text{-}1000\text{ MPa}$) and toughness (elongation $10\%\text{-}20\%$), and is suitable for scenes with high stress or impact, such as military armor-piercing projectile cores. The strength and toughness of tungsten -nickel-copper alloy are slightly inferior (tensile strength $700\text{-}900\text{ MPa}$, elongation $5\%\text{-}15\%$), but its non-magnetic properties (copper is paramagnetic) make it more advantageous in scenes with high electromagnetic compatibility requirements (such as MRI equipment). Tungsten -nickel-iron alloy has weak ferromagnetism due to the addition of iron, which may cause slight interference in highly sensitive electromagnetic environments. In terms of thermal conductivity, tungsten-nickel-copper alloy ($120\text{-}150\text{ W/m}\cdot\text{K}$) is slightly higher than tungsten -nickel-iron alloy ($100\text{-}130\text{ W/m}\cdot\text{K}$), and is suitable for occasions that require rapid heat dissipation. In terms of corrosion resistance, tungsten-nickel-iron alloy performs well in humid or chemical environments due to the oxidation resistance of nickel, while the copper component of tungsten-nickel-copper alloy may cause slight corrosion in certain acidic environments.

Processing and cost : The processing performance of tungsten nickel iron alloy is better. The bonding phase of nickel and iron reduces the overall hardness, which is convenient for turning, milling and EDM. The machinability of tungsten nickel copper alloy is slightly inferior. Due to the higher ductility of copper, it may cause sticking or burrs on the machined surface, requiring more precise processing technology. In terms of cost, iron is cheaper and more abundant than copper, making the raw material cost of tungsten

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nickel iron alloy lower, but the processing and quality control costs are similar. The non-magnetic nature of tungsten nickel copper alloy makes it more competitive in some special applications, but fluctuations in copper prices may increase costs.

Application scenarios : Tungsten -nickel-iron alloy is suitable for scenarios that require high strength and toughness, such as aerospace counterweights, military armor-piercing cores, and medical collimators. Tungsten -nickel-copper alloy is more suitable for electromagnetic sensitive environments, such as MRI shielding or precision instrument counterweights, and its non-magnetic nature avoids interference. Tungsten -nickel-iron alloy is more common in the military field, while tungsten-nickel-copper alloy is more widely used in the medical and electronic fields.

Summary of advantages and disadvantages : Tungsten -nickel-iron alloy has advantages in strength, toughness and cost, and is suitable for high-stress applications, but its weak ferromagnetism may limit its use in electromagnetic sensitive scenarios. The non-magnetic nature and higher thermal conductivity of tungsten -nickel-copper alloy make it more advantageous in specific fields, but its strength is slightly lower and its cost is higher.

6.3.2 Comparison with lead-based alloys

Lead-based alloys have long been used for counterweights, shielding and certain industrial applications due to their high density and low cost. However, compared with tungsten-nickel-iron alloys, lead-based alloys have significant deficiencies in performance and environmental friendliness, especially in high-demand fields such as medical and aerospace.

Performance comparison : The density of lead-based alloys (11.34 g/cm^3) is significantly lower than that of tungsten -nickel-iron alloys ($16.5\text{-}18.75 \text{ g/cm}^3$), requiring a larger volume to achieve the same counterweight or shielding effect, which is not suitable for compact design. The tensile strength ($800\text{-}1000 \text{ MPa}$) and toughness (elongation $10\%\text{-}20\%$) of tungsten -nickel-iron alloys far exceed those of lead-based alloys (tensile strength $<50 \text{ MPa}$, low toughness), enabling them to withstand high stress or impact, making them suitable for military armor-piercing cores or aerospace counterweights. The low strength and brittleness of lead-based alloys make them prone to deformation or fracture, limiting their application in dynamic environments. The low thermal expansion coefficient of tungsten -nickel-iron alloys ($4.5\text{-}5.5 \times 10^{-6} / ^\circ \text{C}$) is better than that of lead-based alloys (about $29 \times 10^{-6} / ^\circ \text{C}$), and they remain dimensionally stable under temperature changes. In terms of corrosion resistance, tungsten-nickel-iron alloys benefit from the oxidation resistance of nickel, far exceeding lead-based alloys, which are susceptible to corrosion in humid or acidic environments. In terms of radiation shielding, tungsten-nickel-iron alloys are superior to lead ($Z=82$) in absorbing X-rays and gamma rays due to the high atomic number of tungsten ($Z=74$), especially in high-energy radiation environments.

Processing and cost : The low hardness of lead-based alloys makes them easy to process. They can be formed by casting or simple mechanical processing, and the cost is much lower than that of tungsten -nickel-iron alloys. Tungsten -nickel-iron alloys need to be prepared by powder metallurgy, hot isostatic

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pressing and precision machining (such as CNC or EDM). The processing cost is high, but complex shapes and high precision (tolerance ± 0.01 mm) can be achieved. Lead-based alloys have low processing accuracy and poor surface quality, and are not suitable for high-precision applications. In terms of environmental protection, the toxicity of lead makes it strictly restricted in the medical and civilian fields (such as the RoHS directive), while tungsten-nickel-iron alloys are non-toxic and environmentally friendly, meeting modern safety standards.

Application scenarios : Tungsten -nickel-iron alloys are widely used in medical shielding parts, aerospace counterweights and military components to meet high performance and environmental protection requirements. Lead-based alloys are mainly used in low-cost, low-requirement scenarios, such as industrial counterweights or non-precision shielding, but their application is gradually reduced due to environmental regulations.

Summary of advantages and disadvantages : Tungsten -nickel-iron alloy far exceeds lead-based alloy in density, strength, corrosion resistance and environmental protection, and is suitable for high-performance applications, but the cost is relatively high. Lead-based alloy has low cost and simple processing, but its performance and environmental protection are insufficient, and it is gradually replaced by tungsten-nickel-iron alloy.

6.3.3 Comparison with other high-density materials

In addition to WNiCu and Pb-based alloys, WNiFe also needs to be compared with other high-density materials, such as W-based composites , uranium-based alloys , and high-density ceramics, to assess their competitiveness in specific applications. These materials have their own characteristics in terms of density, performance, and cost.

Performance comparison : Tungsten-based composite materials (such as tungsten-polymer composites) have a lower density ($10\text{--}15\text{ g/cm}^3$) than tungsten -nickel-iron alloys ($16.5\text{--}18.75\text{ g/cm}^3$), and their shielding and counterweight effects are weaker, but they are lightweight and suitable for applications that do not require high density. The strength ($800\text{--}1000\text{ MPa}$) and toughness of tungsten -nickel-iron alloys are better than those of tungsten-polymer composites, and they are suitable for high-stress scenarios. Depleted uranium alloys (density of about 19 g/cm^3) have a slightly higher density than tungsten -nickel-iron alloys, have strong penetration, and are often used in military armor-piercing cores, but their radioactivity and toxicity strictly limit their applications, and special protection is required for processing.

Tungsten -nickel-iron alloys are non-radioactive and suitable for medical and civilian fields. High-density ceramics (such as tungsten carbide, density of about 15.6 g/cm^3) have extremely high hardness, but low toughness and are prone to brittle fracture, making them suitable for wear-resistant coatings rather than main components. The toughness (elongation $10\%\text{--}20\%$) and processability of tungsten-nickel-iron alloys are better than those of ceramics, and they are suitable for parts with complex shapes . In terms of thermal conductivity and corrosion resistance, tungsten-nickel-iron alloy ($100\text{--}130\text{ W/m}\cdot\text{K}$) is superior to tungsten-polymer composites and ceramics, but is slightly inferior to pure tungsten (173

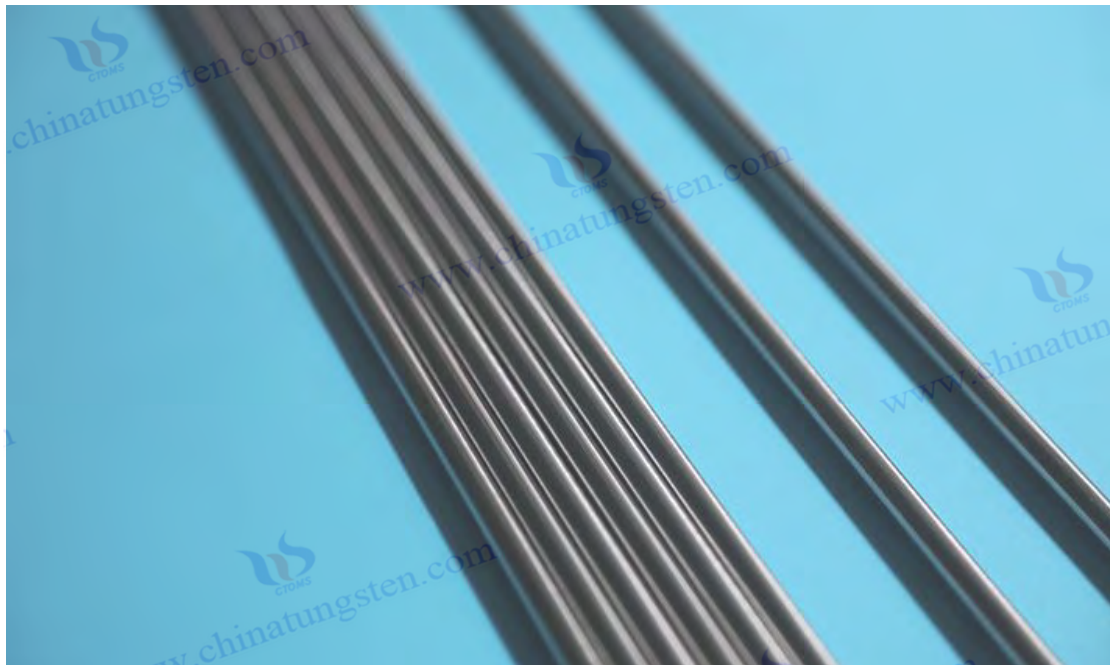
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W/m·K) at high temperatures.

Processing and cost : Tungsten -nickel-iron alloy is formed by powder metallurgy and precision machining. The processing cost is higher than tungsten-polymer composite (can be molded by injection molding), but lower than pure tungsten (high hardness and difficult to process). The processing of depleted uranium alloys requires special equipment and protective measures, and the cost and safety risks are extremely high. The sintering and processing of high-density ceramics (such as diamond grinding) are expensive and limited in shape. Tungsten -nickel-iron alloy has good processing performance, supports turning, milling and 3D printing, and is suitable for the manufacture of complex parts.

Application scenarios : Tungsten -nickel-iron alloy is suitable for aerospace counterweights, medical shielding and military components, taking into account both performance and processability. Tungsten-polymer composites are used for lightweight shielding or low-stress scenarios, depleted uranium alloys are limited to special military applications, and high-density ceramics are used for wear-resistant coatings or tools. Tungsten -nickel-iron alloys strike a balance between performance, environmental protection and processability, and have a wider range of applications.

Summary of advantages and disadvantages : Tungsten -nickel-iron alloy is superior to tungsten-polymer composite and ceramic in density, strength and processability, and is more environmentally friendly than depleted uranium alloy, but may be replaced by other materials in specific scenarios (such as extreme wear resistance or ultra-high density). The comprehensive performance makes it more competitive in the high-performance field.



CTIA GROUP LTD Tungsten Nickel Iron Alloy

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Chapter 7 Impact of Tungsten-Nickel-Iron Alloy Production and Use on the Environment

7.1 Environmental impact during production

Tungsten -nickel-iron alloy involves multiple links such as raw material mining, refining, powder metallurgy, processing and surface treatment, which have a certain impact on the environment. Although tungsten -nickel-iron alloy has environmental advantages over traditional materials such as lead-based alloys, its production process still involves environmental issues such as resource consumption, energy use and waste emissions, which may have potential impacts on soil, water and atmosphere. Driven by the demand for high-performance applications (such as aerospace, military, medical and precision instruments), optimizing production processes to reduce environmental impact has become a focus of industry attention. The following will analyze in detail the environmental impact of tungsten -nickel-iron alloy production in terms of resource mining and energy consumption, as well as waste and emissions.

7.1.1 Resource extraction and energy consumption

Tungsten -nickel-iron alloys relies on the mining and refining of metals such as tungsten, nickel and iron. These processes consume a lot of resources and energy, and are accompanied by potential environmental impacts. As a rare metal, the mining and processing of tungsten is complex and energy-intensive, while the mining of nickel and iron also involves environmental disturbance, leading to land damage and changes in ecosystems.

Environmental impact : Tungsten mining is mainly concentrated in a few countries (such as China and Russia), mostly using open-pit or underground mining methods. The mining process destroys surface vegetation, causing soil erosion and land degradation, which may affect the local ecosystem. Tungsten beneficiation requires the use of large amounts of water and chemical reagents (such as flotation agents, including sulfides or organic compounds). If the wastewater is not properly treated, it may pollute surface water or groundwater. Nickel mining (such as nickel sulfide or laterite nickel ore) also involves land excavation and vegetation destruction, and the smelting process of nickel requires high-temperature smelting, high energy consumption and greenhouse gas emissions. Iron ore mining is large-scale, accompanied by tailings accumulation and water resource consumption, which may lead to eutrophication or heavy metal pollution of water bodies. The production of tungsten -nickel-iron alloy adopts powder metallurgy. Liquid phase sintering (1450-1550°C) and hot isostatic pressing (HIP, 1200-1400°C, 100-200 MPa) require high temperature and high pressure equipment, consume a lot of electricity or natural gas, and increase carbon emissions. In addition, alloy powder preparation (such as atomization) requires high-energy consumption equipment, further exacerbating energy consumption. The energy requirements of these processes mostly rely on fossil fuels, resulting in a high carbon footprint.

Impact Assessment : Mining activities may lead to land occupation and ecological damage, especially in ecologically sensitive areas, requiring strict environmental restoration measures. If the ore dressing wastewater is not treated, it may discharge heavy metals (such as tungsten and nickel) or chemical

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reagents into the water body, affecting the aquatic ecosystem. In terms of energy consumption, the electricity demand for sintering and hot isostatic pressing may account for more than 50% of the total energy consumption of production, increasing greenhouse gas emissions, especially in areas that rely on coal-fired power generation. Global tungsten resources are limited, and over-exploitation may lead to resource depletion and affect long-term sustainability.

Improvement direction : Adopting green mineral processing technology (such as non-toxic flotation agents or dry mineral processing) can reduce wastewater pollution and chemical use. Optimizing mining processes (such as precision blasting) can reduce land damage. Energy efficiency can be improved by using renewable energy (such as wind or solar power) or improving sintering processes (such as low-temperature sintering). Recycling scrap alloys (such as aerospace counterweights or medical shielding parts) can reduce the demand for primary tungsten and nickel and ease resource pressure. Strengthening supply chain management and diversifying tungsten ore sources can reduce the environmental and economic risks brought about by resource scarcity.

7.1.2 Waste and emissions

Tungsten -nickel-iron alloy generates a variety of wastes and emissions, including solid waste, wastewater, waste gas and processing by-products. If these wastes are not properly managed, they may pollute the soil, water and air, affecting the ecological environment and human health. Although the alloy itself is non-toxic, its production process still needs to be strictly controlled to comply with environmental regulations.

Environmental impact : During the beneficiation stage, the tailings of tungsten and nickel ores contain heavy metals (such as tungsten, nickel, iron) and other impurities, which may seep into the soil or water bodies if not properly stacked, causing long-term pollution. During the powder metallurgy process, sintering and hot isostatic pressing may produce waste gases such as carbon dioxide, nitrogen oxides (NO_x) or volatile organic compounds (VOCs), which may cause air pollution if not treated by filtration or adsorption. Processing stages (such as turning, milling or grinding) produce metal chips, cutting fluid waste and polishing waste. The oils or chemical additives contained in the cutting fluid may pollute water bodies or soil. Surface treatment (such as electroplating or chemical cleaning) produces waste liquid containing nickel or acidic substances, which may pollute water bodies or release toxic gases if not properly treated. The potential allergenicity of nickel requires protective measures to be taken during production and processing to avoid health risks caused by contact with dust or waste liquid. In addition, the recycling of scrap alloy parts (such as medical collimators or military bullet cores) may lead to resource waste or heavy metal pollution if it is not standardized.

Impact Assessment : If tailings and wastewater are not treated, they may lead to excessive heavy metals in the soil or water pollution, affecting agriculture and ecosystems. Waste gas emissions increase air pollution, especially in production concentrated areas, which may aggravate regional smog or greenhouse effect. If processing waste and waste liquid are discarded at will, they may pollute groundwater or release harmful substances, affecting the health of surrounding residents. Improper treatment of nickel dust or

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waste liquid may cause occupational health risks, such as skin allergies or respiratory irritation. The low recycling rate of scrap alloys may aggravate resource waste and increase environmental burden.

Improvement direction : The use of closed-loop water treatment systems (such as neutralization precipitation or membrane filtration) can effectively treat mineral processing wastewater and electroplating waste liquid and reduce heavy metal emissions. Tailings can be treated by solidification or backfilling technology to prevent leakage pollution. Waste gas can be treated by high-efficiency filters or catalytic converters to reduce NO_x and VOC emissions. Processing waste can be recycled and reused by classification (such as metal chips back to the furnace) to reduce waste. Strengthen the waste alloy recycling system and develop efficient separation technologies (such as chemical dissolution or electrolysis) to increase the recovery rate of tungsten and nickel. Green cutting fluids or dry processing can be used in the production process to reduce waste liquid generation. In view of the health risks of nickel, protective measures (such as closed operations and protective equipment) need to be strengthened to reduce the risk of worker exposure. Compliance with international environmental standards (such as ISO 14001) can further standardize production and reduce environmental impact.

7.2 Green Manufacturing Technology

The sustainable development of tungsten -nickel-iron production by optimizing production processes, reducing resource consumption and lowering environmental pollution . Tungsten -nickel-iron is widely used in aerospace, military, medical and precision instrument fields due to its high density, excellent mechanical properties and corrosion resistance, but its production process involves high energy consumption and potential environmental pollution. Green manufacturing technology reduces energy consumption, waste emissions and environmental impact through environmentally friendly preparation methods and energy-saving technologies, while improving production efficiency and economic benefits. The following will discuss in detail the application of environmentally friendly preparation methods and energy-saving technologies in the production of tungsten-nickel-iron.

7.2.1 Environmentally friendly preparation method

Environmentally friendly preparation methods reduce negative impacts on the environment by optimizing raw material processing, alloy production and post-processing processes. In the raw material processing stage, efficient screening and purification technologies are used to abandon the strong acid and alkali chemicals used in large quantities in traditional processes, and instead use physical sorting combined with biological leaching to extract tungsten, nickel, iron and other raw materials, which can not only reduce chemical pollution, but also improve raw material utilization and reduce resource waste .

Green smelting technology is introduced in the alloy production process. By precisely controlling the temperature, atmosphere and material ratio in the furnace, efficient energy utilization is achieved and carbon emissions caused by fuel consumption are reduced. At the same time, a closed-loop circulation system is used to purify the waste gas generated during the production process and reuse it. The waste slag is crushed and ground and then reused as auxiliary material in production, which greatly reduces the

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amount of waste generated .

In the post-treatment process, environmentally friendly cleaning agents are used to replace traditional cleaning agents containing phosphorus and heavy metals, while ensuring the cleanliness of the alloy surface and avoiding wastewater pollution to soil and water bodies. These methods can maintain the high performance of tungsten -nickel-iron alloys while reducing the use of chemicals, waste generation and pollution emissions .

This preparation method that takes into account both environmental protection and performance enables it to meet the needs of fields such as aerospace and medical care that have extremely high requirements for material performance and environmental protection, laying a solid foundation for the sustainable application of tungsten-nickel-iron alloy.

Environmentally friendly preparation technology :

- **Green beneficiation technology** : Traditional tungsten and nickel ore beneficiation uses sulfur-containing or organic flotation agents, which are prone to produce harmful wastewater. Green beneficiation uses non-toxic or low-toxic flotation agents (such as fatty acids or bio-based reagents) to reduce heavy metals and chemical pollutants in wastewater. Dry beneficiation (such as airflow separation) can reduce water resource consumption and reduce the burden of wastewater treatment. The closed-loop water treatment system recovers metal ions in beneficiation wastewater through neutralization, precipitation or membrane filtration technology to prevent water pollution.
- **Efficient powder preparation** : Tungsten -nickel-iron alloy is produced by powder metallurgy, and powder preparation is done by atomization or mechanical alloying. Environmentally friendly atomization technology uses inert gas (such as argon) instead of air to reduce oxide inclusions and reduce energy consumption for subsequent purification. Mechanical alloying prepares alloy powder through high-energy ball milling, which can reduce the use of chemical reagents and improve the utilization rate of raw materials. The waste powder recovery system can collect and recycle the dust in production to reduce resource waste.
- **Green sintering process** : Liquid phase sintering (1450-1550°C) is the core step in alloy production. The traditional process uses fossil fuels for heating, which produces a lot of carbon emissions. Green sintering uses plasma sintering (SPS) or microwave sintering, which heats quickly and locally, reducing heat loss and exhaust emissions. Using clean energy (such as solar or wind power) to power the system can further reduce the carbon footprint. Optimizing the sintering atmosphere (such as high-purity argon) reduces oxide generation and reduces the need for exhaust gas treatment.
- **Environmentally friendly post-processing** : Mechanical processing and surface treatment (such as electroplating or chemical cleaning) often produce waste liquid and waste materials. Green processing uses dry cutting or environmentally friendly cutting fluids (such as water-based or bio-based cutting fluids) to reduce the discharge of harmful waste liquids. Electroplating waste liquid is treated by ion exchange or electrochemical recovery technology

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to recover nickel or other metals and reduce environmental pollution. Surface polishing can use laser polishing or ultrasonic polishing to replace traditional chemical polishing and reduce the use of chemical reagents.

Environmental benefits : Green mineral processing reduces heavy metal and chemical pollutants in wastewater, protecting water bodies and soil. Efficient powder preparation and waste powder recycling improve resource utilization and reduce the demand for primary tungsten and nickel ores. Green sintering process reduces carbon emissions and waste gas, improving air quality. Environmentally friendly post-processing reduces waste liquid and waste pollution, and improves the sustainability of the production process.

Technical challenges and optimization : Green preparation technology needs to balance performance and cost. The initial investment in environmentally friendly flotation agents and clean energy equipment is high, and costs need to be reduced through large-scale production, such as establishing large-scale joint production lines to achieve resource sharing and cost sharing. Green sintering (such as SPS) requires high equipment precision, and process parameters need to be optimized to ensure alloy density and microstructure uniformity. Parameter optimization models can be constructed with the help of multiple sets of experimental data. The waste liquid recovery system needs to operate efficiently and be equipped with real-time monitoring devices to avoid secondary pollution and improve resource recycling. In the future, the development of low-cost environmentally friendly reagents and intelligent production control systems can further improve the efficiency and feasibility of green preparation and promote the sustainable development of the industry.

7.2.2 Energy-saving technologies

Energy consumption and carbon emissions in the manufacture of tungsten -nickel-iron alloys by optimizing energy use in the production process . Alloy production involves high energy consumption (such as sintering, hot isostatic pressing and machining). The application of energy-saving technologies not only reduces environmental impact, but also reduces production costs and improves economic competitiveness.

Energy-saving technology :

- **High-efficiency sintering technology :** Traditional liquid phase sintering uses resistance furnaces or gas furnaces, which have high energy consumption and low thermal efficiency. Rapid sintering technologies, such as spark plasma sintering (SPS) or microwave sintering, directly heat the powder through high-frequency electric fields or microwaves, shortening the heating time to a few minutes, and reducing energy consumption by 30%-50% compared to traditional sintering (several hours). Low-temperature sintering technology reduces the sintering temperature to 1300-1400°C by optimizing powder particle size and additives (such as nano nickel powder), reducing energy consumption.
- **Hot Isostatic Pressing Optimization :** Hot isostatic pressing (HIP) is used to increase the density of alloys. Traditional processes require high temperature and pressure (1200-1400°C,

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100-200 MPa), which consumes a lot of energy. Energy-saving HIP uses efficient insulation materials and precise pressure control to reduce heat loss and power consumption. Intermittent HIP processes can reduce energy consumption by optimizing the pressurization cycle, shortening the operating time. Using renewable energy (such as wind or solar energy) to power HIP equipment can further reduce carbon emissions.

- **Intelligent processing technology** : Mechanical processing (such as turning and milling) consumes a lot of energy due to the high hardness of the alloy (Vickers hardness 350-400 HV). The intelligent processing system monitors the cutting force and temperature in real time and dynamically adjusts the cutting parameters (such as speed and feed rate) to improve processing efficiency and reduce energy consumption. Dry processing or minimum quantity lubrication (MQL) technology reduces the use of cutting fluid and reduces the energy consumption of cooling and waste fluid treatment. Laser or EDM can achieve high-precision micro-machining, reduce material waste and secondary processing energy consumption.
- **Energy recovery and management** : A waste heat recovery system can be used in the production process to use the waste heat from the sintering furnace or HIP equipment to preheat raw materials or heat the factory, reducing energy waste. The intelligent energy management system optimizes equipment operation time through sensors and data analysis to avoid no-load operation. Factory-level energy audits can identify high-energy-consuming links and formulate targeted energy-saving measures.

Environmental benefits : High-efficiency sintering and hot isostatic pressing technologies significantly reduce electricity and gas consumption and greenhouse gas emissions. Intelligent processing technologies improve material utilization, reduce waste generation, and reduce waste treatment energy consumption. Energy recovery systems improve overall energy efficiency and reduce the carbon footprint of the production process. These technologies make tungsten-nickel-iron alloy production more in line with environmental regulations (such as ISO 14001) and sustainable development goals.

Technical challenges and optimization : The equipment investment cost of energy-saving technologies is high. For example, SPS and intelligent processing systems require high-precision equipment, and the cost needs to be diluted through large-scale production. Low-temperature sintering may affect the properties of the alloy, and the formula and process parameters need to be optimized to ensure strength and density. The efficiency of the energy recovery system is limited by the equipment design, and more efficient heat exchange technology needs to be developed. In the future, the combination of artificial intelligence and Internet of Things technologies can achieve real-time optimization of the production process, further reducing energy consumption and environmental impact.

7.3 Recycling and reuse

Recycling and reuse are important links in the green manufacturing of tungsten-nickel-iron alloys, which can significantly reduce dependence on scarce resources, reduce environmental pollution and production costs. Tungsten -nickel-iron alloys are widely used in aerospace, military, medical and precision instruments due to their high density (16.5-18.75 g/cm³), excellent mechanical properties (tensile strength

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800-1000 MPa) and corrosion resistance. However, the scarcity of tungsten resources and the high energy consumption of the production process make recycling and reuse the key to achieving sustainable development. Through advanced alloy recycling technology and its role in the circular economy, tungsten-nickel-iron alloys can effectively reduce resource waste and environmental impact while improving economic benefits. The following will discuss alloy recycling technology and its role in the circular economy in detail.

7.3.1 Alloy recovery technology

Tungsten -nickel-iron alloy aims to separate and reuse metals such as tungsten, nickel and iron from scrap parts, processing waste or production by-products to reduce the demand for primary resources and reduce environmental pollution. The recycling process involves a combination of physical, chemical and metallurgical technologies to ensure that the purity and properties of the recycled materials meet the requirements of high-performance applications (such as aerospace counterweights or medical shielding parts).

Recycling technology :

- **Physical recycling and sorting** : Waste tungsten -nickel-iron alloy parts (such as aerospace counterweights, medical collimators or military projectile cores) are first processed by mechanical crushing and grinding to produce small particles or powders. Sorting techniques (such as magnetic separation or gravity separation) are used to separate metal from non-metallic impurities in the alloy. Magnetic separation can separate iron and nickel using the weak ferromagnetic properties of the alloy , while high-density tungsten particles can be extracted by gravity separation. Processing waste (such as cuttings or grinding powder) is screened and washed to remove cutting fluids or oils, providing clean raw materials for subsequent processing.
- **Chemical recovery** : Chemical recovery separates tungsten, nickel and iron from alloys through acid or alkaline dissolution processes . For example, nitric acid or hydrochloric acid solutions can dissolve nickel and iron, leaving tungsten oxide (WO_3) or tungstate, which can then be converted into high-purity tungsten powder through a reduction process (such as hydrogen reduction). Nickel and iron can be recovered from the solution by electrochemical deposition or chemical precipitation to produce high-purity metal salts or metal powders. Chemical recovery requires strict control of solution pH and reaction conditions to avoid secondary contamination.
- **Metallurgical recovery** : High-temperature metallurgical techniques (such as arc furnace melting or vacuum melting) can directly melt the scrap alloy and separate tungsten, nickel and iron. Vacuum melting is carried out in an inert atmosphere (such as argon) to reduce oxide formation and improve the purity of the recovered metal. The recovered metal powder can be re-alloyed by powder metallurgy (liquid phase sintering, 1450-1550°C) to ensure that the properties (such as density >99.5%) meet the standards. Hot isostatic pressing (HIP, 1200-1400°C, 100-200 MPa) can further improve the microstructural homogeneity of the recovered alloy.
- **Advanced recycling technologies** : Emerging technologies such as plasma treatment and

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electrochemical recycling can improve recycling efficiency. Plasma treatment uses a high-temperature plasma arc to decompose alloys, quickly separate metal components, and reduce the use of chemical reagents. Electrochemical recycling separates tungsten, nickel, and iron through electrolysis, reducing energy consumption and waste generation. These technologies are suitable for processing complex-shaped scrap parts or applications with high purity requirements.

Environmental and economic benefits : Physical recycling reduces waste accumulation and reduces the risk of soil and water pollution. Chemical and metallurgical recycling increases the recovery rate of tungsten and nickel (up to more than 90%), reduces the mining of primary minerals, and protects natural resources. Advanced recycling technology reduces energy consumption and waste emissions and complies with environmental regulations (such as ISO 14001). Economically, recycling reduces raw material costs (tungsten accounts for 60%-70% of the alloy cost) and improves production efficiency.

Technical challenges and optimization : The recycling process needs to ensure the purity of the metal, and impurities (such as oxygen and carbon) must be removed through multi-stage filtration and refining processes to prevent them from affecting the properties of the alloy. Chemical recycling may produce acidic waste liquid, which requires an efficient waste liquid treatment system (such as ion exchange or neutralization), combined with online pH monitoring and precise control to prevent contamination. The recycling of complex components (such as medical shielding parts) requires efficient sorting technology, which uses spectral recognition to quickly separate alloys from other materials. In the future, the development of automated recycling equipment and intelligent sorting systems can improve efficiency and reduce labor costs. Optimizing chemical recycling processes (such as using green solvents) and combining them with recycling devices can further reduce environmental impact and improve the economic efficiency of recycling.

7.3.2 Roles in the circular economy

Tungsten -nickel-iron alloy plays an important role in the circular economy. Through recycling, reuse and resource circulation, it reduces resource waste, environmental pollution and production costs, and promotes sustainable development. The circular economy emphasizes the efficient use of resources and closed-loop management. The recycling and reuse of tungsten-nickel-iron alloy can transform it from a one-time use to a sustainable and cyclical resource, supporting the green development of aerospace, medical and other fields.

Circular Economy Role :

- **Resource recycling :** The high value of tungsten -nickel-iron alloy (due to the scarcity and high cost of tungsten) makes it an ideal candidate for the circular economy. Waste alloy parts (such as aviation counterweights, military bullet cores or medical collimators) are converted into high-purity tungsten, nickel and iron through recycling technology, and then used to produce new alloys, reducing dependence on primary tungsten ore and nickel ore. Improved recycling rates can significantly reduce land damage and water pollution caused by resource mining.

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- **Waste minimization** : Recycling technologies such as physical sorting and chemical recycling convert processing waste (such as cuttings) and scrap parts into reusable raw materials, reducing solid waste accumulation and environmental pollution. Closed-loop recycling systems maximize resource utilization by returning waste directly to production. For example, the recycling of aerospace counterweights can be reprocessed into similar parts, reducing waste disposal costs.
- **Improved energy efficiency** : The recycling process consumes less energy than primary metal refining. For example, the energy consumption of recycling tungsten powder is about 30%-50% lower than that of refining from tungsten ore. By combining energy-saving technologies (such as plasma recycling or low-temperature sintering), alloy production in the circular economy further reduces carbon emissions and meets green manufacturing goals.
- **Supply Chain Sustainability** : The recycling of tungsten -nickel-iron alloy supports closed-loop supply chain management in the circular economy. By establishing a global recycling network and standardizing recycling processes, manufacturers can ensure a stable supply of resources such as tungsten and nickel, and reduce the risks brought by geopolitical or market fluctuations. This is especially important for tungsten, a scarce resource, which can ease supply chain pressure.

Application and Impact : In the aerospace field, recycled tungsten-nickel-iron alloys can be used to re-prepare counterweights or high-temperature resistant parts, reducing production costs and reducing environmental impact. In the medical field, the recycling of waste shielding parts and collimators can be used to produce new parts in a circular manner, meeting strict environmental and safety standards. In the military industry, recycling core materials can reduce resource waste while reducing the risk of handling sensitive materials. The implementation of the circular economy improves the sustainability of tungsten-nickel-iron alloys, making them more competitive in high-performance applications.

Technical challenges and optimization : The implementation of the circular economy needs to overcome the cost and efficiency bottlenecks of recycling technology. The initial investment in recycling equipment is high, and costs need to be reduced through large-scale production and policy support. The composition of scrap alloys from different sources is complex, and efficient sorting and purification technologies need to be developed to ensure the quality of recycled materials. Supply chain integration needs to strengthen cross-industry cooperation and establish a closed-loop system from waste collection to reuse. In the future, artificial intelligence and big data can optimize the recycling process, predict waste composition and adjust recycling parameters to improve efficiency and material purity.



CTIA GROUP LTD Tungsten Nickel Iron Alloy

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Tungsten Nickel Iron Alloy Introduction

1. Overview of Tungsten Nickel Iron Alloy

Tungsten-nickel-iron alloy is a high-density material with tungsten as the primary component and nickel and iron added as binder phases. Known for its excellent physical and chemical properties, it is widely used in aerospace, military, medical, nuclear industries, and civilian fields. CTIA GROUP LTD offers tungsten-nickel-iron alloy products, including alloy rods, counterweights, radiation shields, and phone vibrators, tailored for various applications.

2. Features of Tungsten Nickel Iron Alloy

High Density: Typically ranges from 16.5 to 18.75 g/cm³.

High Strength: Tensile strength ranges from 700 to 1000 MPa.

Other Characteristics: Exhibits strong radiation absorption, high thermal conductivity, low thermal expansion coefficient, good electrical conductivity, plasticity, weldability, and processability.

3. Tungsten-Nickel-Iron Alloy Grades

Grade	Class 1	Class 1	Class 2	Class 2	Class 3	Class 3	Class 4
Composition (%)	90W 7Ni3Fe	91W 6Ni3Fe	92W 5Ni3Fe	93W 4Ni3Fe	95W 3Ni2Fe	96W 3Ni1Fe	97W 2Ni1Fe
Density (g/cm³)	17.1	17.25	17.50	17.60	18.10	18.30	18.50
Heat Treatment	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering	Sintering
Tensile Strength (PSI)	900~1000		900~1100		920~1100		
Elongation (%)	18~29	17~27	16~26	16~24	10~22	8~20	6~13
Hardness (HRC)	24~28	25~29	25~29	26~30	27~32	28~34	28~36

4. Production Methods for Tungsten Nickel Iron Alloy

The powder metallurgy process involves first mixing tungsten powder, nickel powder, and iron powder; then ball milling and sieving; followed by shaping the mixed powder into blanks using hot pressing, hot isostatic pressing, or vacuum sintering techniques; and finally improving the alloy’s microstructure and properties through heat treatments such as annealing or quenching.

5. Applications of Tungsten Nickel Iron Alloy

In the medical field, tungsten-nickel-iron alloy serves as radiation shields, radiation source containers, collimators, isotope containers, and syringe shields. In scientific research, tungsten alloy is used as heat sinks and for oil drilling and mineral resource exploration.

6. Purchasing Information

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Chapter 8 Frequently Asked Questions and Answers

Tungsten -nickel-iron alloy is widely used in aerospace, military, medical and precision instruments due to its high density (16.5-18.75 g/cm³), excellent mechanical properties (tensile strength 800-1000 MPa, elongation 10%-20%) and corrosion resistance. However, misunderstandings about its performance, production and application, as well as practical problems in technology and application, often trouble users and manufacturers. This chapter aims to clarify common misunderstandings, answer common questions in technology and application, and provide expert advice and solutions to help users better understand and use tungsten -nickel-iron alloy.

8.1 Common Misunderstandings about Tungsten Nickel Iron Alloy

About tungsten -nickel-iron alloys usually stem from incorrect perceptions of their properties, composition, or application scenarios. These misunderstandings may cause users to make inaccurate judgments when selecting materials or designing applications. The following are several common misunderstandings and their clarifications:

Misconception 1 : Tungsten -nickel-iron alloy is completely non-magnetic

Clarification: Tungsten -nickel-iron alloy has weak ferromagnetism (saturation magnetization 0.1-0.3 T) due to the iron content (1%-5%), and is not a completely non-magnetic material. This is different from tungsten-nickel-copper alloy (completely non-magnetic). Weak ferromagnetism has little effect in most applications (such as aerospace counterweights or medical shielding parts), but special attention should be paid in highly sensitive electromagnetic environments (such as MRI equipment). Users can reduce magnetic interference by reducing the iron content or using non-magnetic coatings (such as DLC).

Misunderstanding 2: Tungsten -nickel-iron alloy has the same properties as pure tungsten

Clarification: Tungsten -nickel-iron alloy improves the brittleness and processing difficulty of pure tungsten by adding nickel and iron . Pure tungsten (density 19.25 g/cm³, high hardness) is difficult to machine and is prone to brittle fracture, while tungsten-nickel-iron alloy (density 16.5-18.75 g/cm³) has better toughness (elongation 10%-20%) and processing performance, and is suitable for manufacturing complex-shaped parts (such as medical collimators). However, its density and strength are slightly lower than pure tungsten, and it needs to be weighed according to application requirements.

Myth 3: Tungsten -nickel-iron alloy is completely non-toxic and has no environmental impact

Clarification: Although tungsten nickel iron alloy is more environmentally friendly (non-toxic) than lead-based alloys, nickel is potentially allergenic and long-term contact may cause skin or tissue reactions, requiring biocompatibility testing in medical implant applications. The production process (mining, sintering) involves energy consumption and waste emissions, which may have an impact on the environment (such as tailings pollution). Green manufacturing and recycling technologies can reduce

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these impacts, but they are not completely free of environmental burdens.

Myth 4: Tungsten -nickel-iron alloy is low-cost and easy to mass-produce

Tungsten -nickel-iron alloy is relatively high, which is mainly due to the scarcity of tungsten resources and the complexity of its refining process. Tungsten ore is difficult to mine, and the selection and purification requires multiple complex processes. In addition, a large amount of energy and reagents are consumed during the refining process, which further increases the cost of raw materials. In the production and processing stage, powder metallurgy requires high-precision equipment to ensure the mixing uniformity and molding quality of the powder, and precision machining (such as CNC, EDM) not only relies on high-energy consumption equipment, but also requires the use of special wear-resistant tools. The loss and replacement of these tools also increase the cost. In contrast, steel or lead resources are abundant, the refining and processing technology is mature and simple, and the production cost is much lower than that of tungsten -nickel-iron alloy, which limits the application of tungsten -nickel-iron alloy in some low-budget fields. Although optimized processes (such as additive manufacturing) can reduce material waste and processing steps, and recycling can also reduce dependence on primary resources, thereby reducing costs to a certain extent, in order to achieve large-scale production and significantly reduce costs, breakthroughs in material formulation, production equipment and process technology are still needed.

8.2 Common Problems in Technology and Application

Tungsten -nickel-iron alloy may encounter a variety of technical problems during production and application, involving material properties, processing difficulty and application environment. The following are common problems and their causes:

Problem 1 : Cracks or surface defects during machining

Cause: The high hardness (Vickers hardness 350-400 HV) and moderate toughness of tungsten -nickel-iron alloys make machining difficult. High-speed cutting or improper cutting parameters may lead to stress concentration and cause microcracks. Microstructure inhomogeneities (such as pores or inclusions) may also cause surface defects. Impact: In aerospace counterweights or medical collimators, cracks may reduce component reliability and accuracy.

Problem 2: Alloy performance is unstable or does not meet expectations

Cause: Improper sintering temperature (1450-1550°C) or atmosphere control during production may lead to increased porosity (>1%) or component segregation (such as uneven distribution of nickel and iron). Insufficient raw material purity (impurities such as oxygen and carbon) may also reduce strength or toughness. Impact: In military armor-piercing cores or precision instrument damping blocks, unstable performance may lead to failure or reduced accuracy.

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Issue 3: Biocompatibility issues in medical applications

Reason: Nickel's potential allergenicity may cause allergic reactions in long-term implants (such as interventional weights) or skin contact. Improper surface treatment (such as peeling of the electroplating layer) may release nickel ions. Impact: May limit the use of alloys in medical implants or surgical robot components.

Problem 4: Magnetic interference in high-sensitivity applications

Cause: The weak ferromagnetism of the alloy (due to the iron content of 1%-5%) may cause slight interference in a highly sensitive electromagnetic environment (such as MRI equipment or photolithography), affecting the accuracy of the equipment. Impact: Additional processing is required in precision instruments or medical equipment to meet electromagnetic compatibility requirements.

Problem 5: Excessive production costs

Reasons: Tungsten resources are scarce and refining is complex. Powder metallurgy and hot isostatic pressing (HIP) require high-energy consumption equipment. Precision machining requires high-wear-resistant tools (such as CBN), which pushes up overall costs.

Impact: Limits the promotion of alloys in cost-sensitive areas, such as civilian consumer goods.

8.3 Expert advice and solutions

In response to the above misunderstandings and problems, experts put forward the following suggestions and solutions to optimize the production and application of tungsten -nickel-iron alloy:

For processing cracks and defects

- Recommendation: Optimize cutting parameters (such as low cutting speed, appropriate feed rate) and use highly wear-resistant tools (such as CBN or diamond tools). Use dry machining or minimum quantity lubrication (MQL) to reduce thermal stress.
- Solution: Eliminate porosity and ensure a homogeneous microstructure by hot isostatic pressing (HIP, 1200-1400°C, 100-200 MPa) before production. Perform non-destructive testing (such as ultrasonic or X-ray testing) after processing to identify potential defects.

For unstable performance

- Recommendation: Strictly control sintering process parameters (such as temperature 1450-1550°C, argon atmosphere), ensure density >99.5%. Use high-purity raw materials (tungsten purity >99.9%) and verify the composition by XRF or ICP-AES.
- Solution: Combine metallographic analysis and SEM-EDS to check the microstructure, optimize the powder particle size and nickel-iron ratio (such as 90W-7Ni-3Fe) to improve performance consistency. Heat treatment (such as annealing, 800-1000°C) can eliminate internal stress.

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Regarding biocompatibility issues

- Recommendation: Reduce nickel content (to 2%-5%) or use biocompatible coatings (such as DLC or TiN) to reduce nickel ion release. Perform ISO 10993 biocompatibility testing before medical application.
- Solution: Surface treatment with electroless nickel or PVD coating for enhanced corrosion resistance and biosafety. Develop nickel-alternative binder phases (such as tungsten-nickel-copper alloys) for sensitive medical applications.

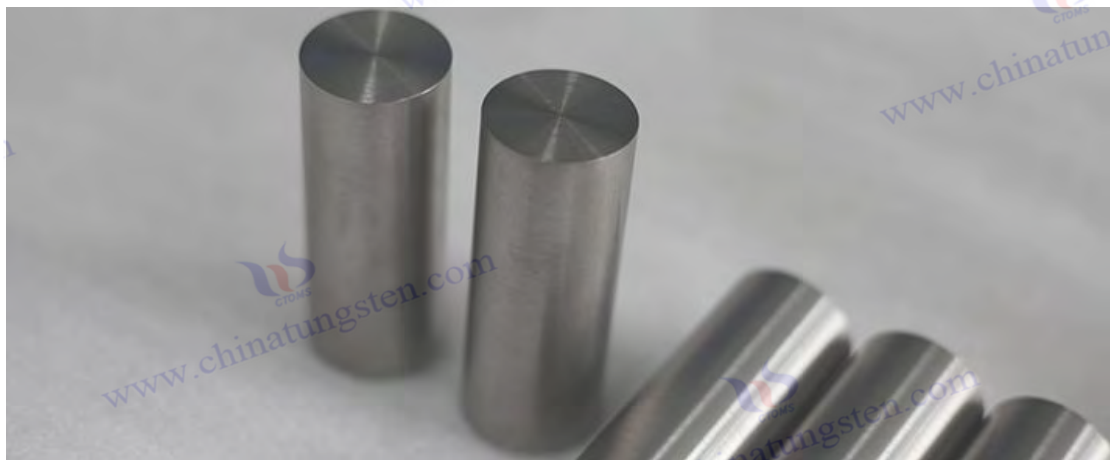
For magnetic interference

- Recommendation: Optimize the alloy formula, reduce the iron content (to 1%-2%) or use tungsten -nickel-copper alloy instead to reduce magnetism.
- Solution: Apply non-magnetic coating (such as DLC) or demagnetization treatment (such as high temperature annealing) to reduce the magnetization intensity. Verify the magnetic properties through vibrating sample magnetometer (VSM) after production to ensure compliance with electromagnetic compatibility requirements.

For high cost

- Recommendations: Use green manufacturing technology (such as plasma sintering or microwave sintering) to reduce energy consumption. Develop efficient recycling technology to recycle waste alloys (such as aviation counterweights) to reduce raw material costs.
- Solution: Introduce additive manufacturing (such as SLM) to produce complex parts to reduce material waste and processing costs. Optimize the supply chain, diversify tungsten resource sources, and reduce market volatility risks.

Comprehensive suggestions : Manufacturers should establish a green production system that complies with ISO 14001 environmental standards and promote a circular economy by combining recycling technology. Users need to clarify application requirements (such as electromagnetic compatibility or biocompatibility) when selecting tungsten -nickel-iron alloys, and work with suppliers to optimize formulations and processes to ensure a balance between performance and cost.



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Appendix: Tungsten Nickel Iron Alloy Glossary

The following is a glossary of terms related to tungsten-nickel-iron alloys, presented in a table format, covering key terms and their definitions in the fields of production, performance, testing and application, aiming to help readers accurately understand and use professional terms.

The term	Definition
High-Density Alloy	An alloy with tungsten as the main component (usually 85%-97%) and added with nickel, iron and other binding phases. It has high density (16.5-18.75 g/cm³) and excellent mechanical properties. It is widely used in counterweights, shielding and military applications.
Powder Metallurgy	The technology of preparing metal materials by mixing metal powders, pressing and high-temperature sintering is used to produce tungsten - nickel-iron alloys, ensuring high density and uniform microstructure.
Liquid Phase Sintering	During the sintering process, the binding phase (such as nickel and iron) melts to form a liquid phase, which promotes the bonding of tungsten particles. It is usually carried out at 1450-1550°C to increase the density of the alloy (>99.5%).
Hot Isostatic Pressing	Densification of the alloy is carried out at high temperature (1200-1400°C) and high pressure (100-200 MPa) to eliminate porosity and improve mechanical properties and microstructural homogeneity.
Tensile Strength	The maximum ability of a material to resist fracture under tensile load. The tensile strength of tungsten nickel iron alloy is usually 800-1000 MPa, reflecting its high strength characteristics.
Elongation	The percentage of plastic deformation of a material before tensile fracture. The elongation of tungsten-nickel-iron alloy is usually 10%-20%, indicating its toughness.
Vickers Hardness	The Vickers hardness of tungsten-nickel-iron alloy is usually 250-400 HV, which reflects its wear resistance.
Coefficient of Thermal Expansion	The dimensional change rate of the material under temperature change, the CTE of tungsten-nickel-iron alloy is $4.5-5.5 \times 10^{-6} / ^\circ \text{C}$, indicating its excellent dimensional stability.
Thermal Conductivity	The material's ability to conduct heat. The thermal conductivity of tungsten-nickel-iron alloy is 100-130 W/m·K, which is suitable for high-temperature heat dissipation applications.
Corrosion Resistance	The material's ability to resist chemical attack. Tungsten-nickel-iron alloy benefits from nickel's oxidation resistance and performs well in humid or acidic environments.
Weak Ferromagnetism	Tungsten -nickel-iron alloy has slight magnetism due to its iron content (1%-5%), with a saturation magnetization of 0.1-0.3 T, which needs to be controlled in electromagnetic sensitive applications.

X-Ray Fluorescence	Non-destructive testing technology for analyzing alloy composition, verifying tungsten, nickel and iron content with an accuracy of $\pm 0.2\%$.
Inductively Coupled Plasma Atomic Emission Spectroscopy	High-precision analysis of alloy composition, used to detect trace impurities (such as oxygen, carbon).
Scanning Electron Microscope	A microscopic technique used to observe the microstructure and surface morphology of alloys, often combined with energy dispersive spectroscopy (EDS) to detect component distribution.
Counterweight	Components made of high-density materials are used to adjust the center of gravity or balance of equipment, such as aerospace counterweights or surgical robot joint counterweights.
Armor-Piercing Core	High-density, high-strength materials such as tungsten-nickel-iron used in military ammunition to penetrate armored targets.
Radiation Shielding	Using high-density materials to absorb X-rays or gamma rays to protect personnel and equipment is common in medical CT/MRI equipment and nuclear energy fields.
Collimator	used in radiotherapy equipment to control the direction and range of radiation beams due to its high density and processability.
Additive Manufacturing	Technologies for manufacturing complex-shaped components by layer-by-layer deposition of materials (e.g. Selective Laser Melting, SLM) are used to produce customized WNiFe components.
Circular Economy	The recycling technology of tungsten-nickel-iron alloy supports the sustainable development of the economic development model that reduces waste through recycling, reuse and resource circulation.
Green Manufacturing	Adopt environmentally friendly processes and technologies (such as green ore dressing and low-temperature sintering) to produce alloys to reduce energy consumption and environmental pollution.
Biocompatibility	to not cause adverse reactions when in contact with human tissue . Tungsten-nickel-iron alloys are tested to ISO 10993 for medical applications.
Electromagnetic Compatibility	The ability of a material or component to work normally in an electromagnetic environment without causing interference. Tungsten-nickel-iron alloys need to optimize weak ferromagnetism to meet EMC requirements.

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