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Development Status and Prospects of Advanced Copper Alloy

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Abstract: Based on the typical demand for advanced copper alloys by emerging industries and major engineering projects such as electrical engineering, electronics, fifth-generation communications, new energy vehicles, aerospace, and rail transit, this paper systematically summarizes the current status of international and domestic copper alloy industries, including high-strength and high-conductivity copper alloys, wear- and corrosion-resistant copper alloys, elastic copper alloys with ultrahigh strength, advanced copper matrix composites, and high-precision copper alloy wires and foils. The typical market demand for advanced copper alloys is analyzed; additionally, medium- and long-term development goals and key technologies of copper alloy materials in China are proposed. Moreover, suggestions for industrial development are presented, including the promotion of the overall planning and integrated development of production, research, application, and management; enhancement of equipment development, technology development, and market expansion abilities; improvement in the research and formulation of product standards; and establishment of a training system for young scientists and technicians. This study is expected to promote the green, high-end, and intelligent development of advanced copper alloy materials in China through improvements in independent innovation systems pertaining to copper alloy materials, equipment, technology, and industrialization, thereby fulfilling the demands of the national economy and national defense construction.
Keywords: copper alloy; high strength; high precision; functional application

1 Introduction

Policy documents such as the *Outline of the National Medium- and Long-term Science and Technology Development Plan* and the *New Material Industry Development Guide* state that new-generation information technology, advanced rail transit equipment, aerospace equipment, energy-saving and new-energy vehicles, and

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other industries are key development high-technology fields in China. High-performance copper alloys exhibit excellent properties such as high electrical conductivity, high thermal conductivity, high strength, high corrosion resistance, platability, and workability [1]; hence, they are indispensable for the development of the abovementioned fields.

China ranks first in terms of domestic copper production and consumption. Based on the overall output and imports of various typically used copper materials, the domestic satisfaction of typically used copper materials has reached 96%. Advanced copper alloy materials and components are vital to national security, major projects, and economic construction. However, various high-performance copper alloy materials rely significantly on imports, such as new high-strength and high-conductivity copper alloy strips, ultrafine wires, and ultra-thin strips.

The development of advanced copper alloy materials and their high-efficiency, short process preparation, and processing technologies facilitates the development of strategic emerging industries and advances China from a “material-quantity country” to a “material-quality country.” First, the application of copper alloys for major national projects and emerging industries is presented herein. Subsequently, the development and application status of copper alloy materials in various fields are presented. Additionally, medium- and long-term development goals and recommendations for advanced copper alloy materials are proposed based analyzing the development trends of and typical market requirements for advanced copper alloy materials.

2 Application status of copper alloy materials in China and abroad

Owing to the rapid progress of high-technology industries, new materials that exhibit ultrahigh performance, high purity, and high iteration have been developed [2]. Consequently, more requirements have been imposed for the integration, functionality, miniaturization, and reliability of related products. As core conductor materials, advanced copper and copper alloys are used extensively in the lead frame of very large-scale integrated circuits in the electronic information industry, electronic countermeasures, radar and high-power microwave tubes for defense equipment, high-pulse magnetic field conductor materials, overhead wires, large-power frequency modulation, speed regulation asynchronous traction motor guide bars, end-rings for high-speed rail transit, resistance welding electrodes, battery materials, charging piles elastic materials for new energy vehicles, continuous casting machine molds, electric vacuum devices for the metallurgical industry, switch contact bridges for electrical engineering, and various types of wires.

2.1 High-strength and high-conductivity copper alloy

High-strength and high-conductivity copper alloys are primarily used in integrated circuit lead-frame strips, rail transit contact wires and high-voltage electrical contacts. More than one hundred types of high-strength and high-conductivity copper alloy materials exist in the international market, where the most extensively used ones include Cu–Fe–P-, Cu–Ni–Si-, and Cu–Cr–Zr-based alloys.

Different grades of Cu–Fe–P- and Cu–Ni–Si-based alloys have been developed abroad, such as C19400 (CuFeP) and C70250 (CuNiSi) by Universal Metal Products Co., Ltd. of the United States, TAMAC194 (CuFeZnP) by Mitsubishi Shindoh Co., Ltd. of Japan, EFTEC6 (CuFeP) by Furukawa Electric Co., Ltd. of Japan, KLF5 (CuFeSnP) and KLF118 (CuNiSiZn) of Kobe Steel Co., Ltd. of Japan, and NKC114 (CuNiSiZn) of Nikkei Metal Co., Ltd. of Japan. Meanwhile, the most extensively used lead frame strips currently are medium-strength and high-conductivity Cu–Fe–P alloys (such as C19400 and KFC) developed by Universal Metal Products Co., Ltd. of the United States; these alloys exhibit medium strength, high electrical conductivity, and high thermal conductivity, as well as good solderability, wettability, and workability, while being inexpensive. Chinalco Luoyang Copper Co., Ltd., China Copper Huazhong Copper Co., Ltd., Ningbo Xingye Shengtai Group Co., Ltd., and Ningbo Boway Alloy Material Co., Ltd. have realized the commercial production of C19400 alloy and dominated the domestic market share. Moreover, domestic universities and enterprises have performed collaborative research to improve the softening resistance temperature by approximately 50 °C for ensuring the comprehensive performance of Cu–Fe–P alloy materials [3]. Meanwhile, Ningbo Xingye Shengtai Group Co., Ltd., Chinalco Luoyang Copper Co., Ltd., Ningbo Boway Alloy Material Co., Ltd., and Ningxia Dongfang Tantalum Co., Ltd. have realized the industrialization of the C70250 alloy strip.

Cu–Cr–Zr-based alloys are ideal for fabricating high-speed rail transit contact wires and lead frames of very large-scale integrated circuits. The PHC-120 contact wire developed by Nagawa Co., Ltd., Japan is based on this type of alloy. In recent years, US, Japanese, and German companies have successively developed heat-resistant Cu–Cr–X series alloy lead frame strips, e.g., C18160 of KME Group, C18080 of Wieland Group, C18141 of

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Mitsubishi Shindoh Co., Ltd., with strengths of 540–630 MPa and theoretical conductivities of 79%–84% of the copper specified as the International Annealed Copper Standard (IACS). Systematic research pertaining to the composition optimization and structural control of Cu–Cr–Zr alloys has been performed [4]. Ningbo Boway Alloy Material Co., Ltd. has realized the industrialization of Cu–Cr–Zr alloy strips with independent intellectual property rights.

2.2 Wear and corrosion resistance copper alloy

Typically used wear- and corrosion-resistant copper alloys include tin bronze, aluminum bronze, manganese white copper, and complex brass. The tensile strengths of the casting are 400–500 MPa, the hardness is 100–200 HBS (Brinell hardness), the elongations are 6%–10%. Meanwhile, the tensile strengths of the extruded material can reach 600 MPa, and the hardness can exceed 200 HBS. Major foreign manufacturers of these alloys are Japan's Sambo Copper Co., Ltd. and Sumitomo Heavy Machinery Industry Co., Ltd., whereas major domestic manufacturers are Chinalco Luoyang Copper Co., Ltd. and Luoyang Shuangruidate Copper Co., Ltd.

Cu–Ni-based corrosion-resistant copper alloys used in marine engineering are primarily B10 (Cu–10Ni–1Fe–1Mn) and B30 (Cu–30Ni–1Fe–1Mn) alloys. The maximum diameter of seamless corrosion-resistant copper–nickel alloy drainage pipes for marine engineering produced in Germany and South Korea exceeds 520 mm, and the thinnest wall thickness is 0.7 mm. The domestic development of large-diameter corrosion-resistant copper–nickel alloy pipes began later compared with the abovementioned countries, and problems of unstable corrosion resistance and short service life were encountered. Some high-end corrosion-resistant Cu–Ni–Fe alloy pipe products rely on imports. The tensile strength of Cu–Ni–Sn-based alloys can reach 1000 MPa, and its corrosion resistance is excellent. Their corrosion resistance in seawater or acidic, oil, and gas environments and their wear resistance under high load conditions are better than those of beryllium copper and aluminum bronze. Currently, all high-end ultrahigh-strength Cu–Ni–Sn alloys used in China are imported. Among them, products manufactured by the Materion Group of the United States, Nagaki Precision Machinery Co., Ltd. of Japan, and Kraal Special Metals Co., Ltd. of France are leading the market. Meanwhile, domestic institutions are collaborating with each other to investigate continuous casting technology, build casting billets equipment under a specific casting environment, build a thermo–mechanical treatment system, as well as investigate the deformation microstructures, internal stress distribution characteristics, and control technology of the Cu–Ni–Sn alloy to provide a foundation for the localization of this alloy .

2.3 Ultrahigh-strength elastic copper alloy

An ultrahigh-strength elastic copper alloy generally refers to a copper alloy with a strength of 1000 MPa or higher and an elastic modulus of 125 GPa or higher. Elastic copper alloys used for high-reliability connectors include primarily beryllium copper. The production and application of beryllium copper materials have reached a high level in developed industrial countries; nonetheless, related equipment and production technology are still being developed. In particular, in the United States (represented by the Materion Group) and Japan (represented by Nagaki Seiki Co., Ltd.), the production scale of the enterprise is enormous, and the production technology and equipment level are ranked first in the world.

Beryllium copper contains beryllium, which is a highly toxic substance. Furthermore, its stress relaxation rate increases significantly at temperatures beyond 150 °C, causing the contact pressure of the elastic components in the working state to change easily, thereby resulting in connector failure. The development of a new type of environmentally friendly, ultrahigh strength, high stress relaxation resistance, good formability, and high reliability conductive elastic copper alloy has become a research focus for elastic materials. Copper alloys such as Cu–Ni–Mn, Cu–Ti, and Cu–Ni–Sn alloys are age-strengthening Cu alloys. After thermo–mechanical treatment, they can yield high strength and elasticity comparable to those of beryllium copper, as well as superior corrosion resistance and stress relaxation resistance [5,6]. These alloys have been investigated and developed by companies in France, the United States, and Japan, and have partially replaced the industrial applications of beryllium copper. Some domestic copper processing enterprises are trial-manufacturing Cu–Ti alloy products; however, because the key processing and preparation technology for large-scale production are lacking a comprehensive breakthrough, existing Cu–Ti alloy materials cannot be self-sufficient.

2.4 Advanced copper matrix composites

Advanced copper-based composite materials are key materials for liquid hydrogen/liquid oxygen rocket engine linings, ultrahigh voltage switches, electrodes, and other components. The introduction of carbon nanotubes and graphene as well as the development of high-strength, high-conductivity carbon nanotube/graphene-reinforced copper-based composite materials have further propelled the research and development of high-conductivity copper-based composite materials domestically and abroad. Copper-based composite samples prepared in laboratory exhibit a tensile strength greater than 500 MPa and an electrical conductivity of 115% IACS. In terms of anti-electromagnetic shielding copper-based composite materials, Japanese companies have developed a series of CFA alloys. For example, CFA95 has a shielding effect of 50–80 dB for magnetic fields, a shielding effect of more than 80 dB for electric fields, and an electrical conductivity of 60%–70% IACS. Meanwhile, domestic enterprises such as Shaanxi Sirui New Materials Co., Ltd. and Ningbo Jintian Copper (Group) Co., Ltd. are building Cu–Fe alloy manufacturing bases.

In terms of high-strength, high-conductivity, and high-temperature softening resistance, copper-based composite materials, SCM Metal Products Co., Ltd. of the United States has developed various Cu–Al_2O_3 dispersion-strengthened copper alloy grades (such as C15710, C15720, and C15760), which are mass produced. The maximum heat-resistance temperature of the Cu–Al_2O_3 dispersion-strengthened copper alloy was reported to be 900 °C [7], and it is primarily used to fabricate electric welding electrodes, medical imaging devices, and electric vacuum devices. Chinalco Luoyang Copper Industry Co., Ltd., General Research Institute for Nonferrous Metals Engineering Institute Co., Ltd., and other domestic institutions have launched independent research and development of dispersion-strengthened copper alloy products that are primarily used for welding electrodes for automobile coated steel plates, battery nickel sheets, aluminum and aluminum alloys, etc. In addition, some special functional copper-based composite materials have been applied, e.g., anti-arc ablation Cu–Cr contact materials; high thermal conductivity, low coefficient of thermal expansion Cu–W electronic packaging materials; as well as ultrahigh-strength and high-conductivity Cu–Nb composite materials whose tensile strength at room temperature and electrical conductivity can exceed 1400 MPa and 70% IACS, respectively.

2.5 High-precision copper alloy wires and foils

With the constantly increasing penetration rate of microelectronics and ultramicroelectronics, new-generation mobile communications, intelligent robots, and other products, the demand for ultrafine high-performance copper wire and high-performance ultrathin copper foil is increasing. In terms of fine wires, the supply and demand of copper wires with different specifications differ significantly in the domestic market. The supply of copper wires with a diameter of 0.04 mm or more exceeds demand; its price is low and competition is fierce. Meanwhile, the domestic demand for ultrafine copper wires (0.015–0.04 mm) is greater than the production capacity, and more than 60% are imported. Ultrafine copper wires with a diameter of less than 0.015 mm are imported. In recent years, some domestic manufacturers have begun the research and development of copper microwires. However, owing to equipment and technology limitations, the product yield rate is low, and the performance is uneven; hence, the requirements of the microelectronics industry cannot be fulfilled.

In terms of ultrathin foils, many domestic high-grade copper clad laminates and printed circuit board manufacturers require rolled copper foils with high flexibility and high mechanical strength. Most of them are supplied by Nikkei Metal Co., Ltd. and Fukuda Metal Foil Industry Co., Ltd., Universal Metal Products Co., Ltd., Hitachi Wire Co., Ltd., and other foreign companies. Currently, a tensile strength of $\geqslant$ 500 MPa can be achieved in highly flexible copper foils when the foil thickness is $\leqslant$ 33 μm. Meanwhile, after annealing them at 135 °C for 30 min, their tensile strength is $\geqslant$ 150 MPa, elongation $\geqslant$ 10%, and number of deflection $\geqslant 7.6 \times 10^8$ times. Domestic enterprises such as China's Albetter Copper and Aluminum Co., Ltd. and Lingbao Huaxin Copper Foil Co., Ltd. of the nonferrous metal industry can mass produce high-quality rolled copper foils of certain specifications. In terms of the surface treatment of rolled copper foils, domestic companies are only capable of performing simple ashing treatments, while blackening treatment technology is still being developed.

3 Analysis of domestic application demand of advanced copper alloy materials

3.1 High-strength and high-conductivity copper alloy

In recent years, breakthroughs have been realized in the industrialization technology of high-strength and high-conductivity copper alloys, such as copper–magnesium, copper–silver, and copper–chromium alloys. When their electrical conductivities are maintained above 80% IACS, their strengths are improved significantly compared with that of pure copper. As such, they have been used extensively in the lead frames of very large-scale

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integrated circuits, contact wires for electrified railway contacts, and high-end precision wires and cables to achieve improved performances [8]. For example, the tensile strength of the high-strength and high-conductivity Cu–Ni–Si–(Co) alloy is 700–900 MPa, and the electrical conductivity is 45%–55% IACS [9]. Furthermore, some domestic copper processing enterprises have begun the trial production of this alloy and provided a small market supply; this alloy is expected to be used extensively after 2020.

High-strength and high-conductivity Cu–Cr–Zr-based alloys are used in rail transit contact network cables, aerospace cables, large-scale integrated circuit lead frames, automotive industry and electronic control systems, welding electrodes, high-pulse magnetic-field conductors, and large high-speed turbine generator rotor wires. Domestic high-speed railway contact wires with speeds less than 300 km/h primarily include Cu–Ag wires, Cu–Sn wires, and Cu–Mg wires, which have achieved self-sufficiency; high-speed railway contact wires with speeds above 380 km/h adopt trial Cu–Cr–Zr alloy contact wires, including the high-speed test section of Zaozhuang to Bengbu of the Beijing–Shanghai high-speed railway and the high-speed test section of Taiyuan North to Yuanping West of the Dalian–Xi'an high-speed railway. The railway industry standard TB/T2809—2017 *Copper and Copper Alloy Contact Wire for Electrified Railways* [10] stipulates the product standard of Cu–Cr–Zr-based alloy contact wires, thereby facilitating subsequent promotion and application.

A new generation of electronic information technology integrated circuit lead frames and future flexible power grid materials are urgently required for the fabrication of high-conductivity and high-strength Cu–Cr–Zr alloy plates/strips/foils. The lead frame strip is the chip carrier of the integrated circuit and is an important basic material in the electronic information industry. It is estimated that by 2035, Cu–Cr alloys can replace more than 60% and more than 30% of typical materials used in high-speed railway contact wire and lead-frame copper alloy applications, respectively.

3.2 Wear- and corrosion-resistant copper alloy

Corrosion-resistant copper alloys are used extensively in condensers, heat exchanger tubes, and various high-strength corrosion resistance parts (valve bodies, flanges, joints, etc.) in seawater desalination, ships, offshore oil platforms, and other fields. With the rapid development of domestic aerospace and machinery manufacturing industries, the performance requirements and demands for high-strength as well as wear-, corrosion-, and heat-resistant copper alloys for aero engines, high-speed bearings, and other components have increased significantly. The tensile strength of the Cu–Ni–Sn-based alloy can reach 1000 MPa, and its corrosion resistance is better than that of beryllium copper and aluminum bronze. It is a key basic material for aviation, heavy-duty equipment, the petrochemical industry, high-end computer numerical control machine tools, and robots. This type of material is used in objects such as civil aviation aircraft landing gears, airfoil control bearings, bushings and hydraulic system wear resistance parts, heavy equipment, computer numerical control machine tools, automobile valve guides, cam rolling pins, roller bearings, hydraulic plunger pump cylinders, valve plates, plungers, bushing, abrasion enhancement plates, and forming rollers/punches.

3.3 Ultrahigh-strength elastic copper alloy

Ultrahigh-strength elastic copper alloys generally require a tensile strength of ⩾ 1000 MPa and an elastic modulus of ⩾ 130 GPa. For beryllium copper (such as QBe2 and C17200) plate and strip products, 60% are used to manufacture elastic components, such as diaphragms, bellows, generator brush springs, relay springs, spring contact sheets, circuit breaker springs, and various types of springs for aviation instruments; they are also used in the manufacture of precision instruments, bearings, gears, roller sleeves for double-roll continuous cast-rolling aluminum slabs, special non-sparking tools, etc., as well as constitute a broad market for electric vehicle charging piles and communication equipment for marine engineering. Currently, the shortage of beryllium copper plates and strips in the world is a concern. The global annual demand is increasing at a rate of approximately 12%, whereas the domestic annual demand is growing at a rate of 20% to 39%; meanwhile, high-precision plates and strips (thickness of less than 0.4 mm) are still being imported.

In recent years, elastic copper alloys with ultra-high strength have developed in the direction of environmentally-friendliness and high stress relaxation resistance, e.g., Cu–Ni–Co–Si-, Cu–Ti-, and Cu–Ni–Sn-based alloys. Domestic researchers discovered that the Cu–Ni–Co–Si alloy can reach a tensile strength of 1086 MPa and an electrical conductivity exceeding 30% IACS after multi-stage thermo-mechanical treatment [11]. Titanium bronze possesses high strength and elasticity, excellent wear resistance, and non-magnetic properties; additionally, it affords ease of solder and electroplating and does not produce sparks when impacted. It can be used to fabricate high-strength, high-elasticity, and high-wear resistance components, such as electrical switches, relay elastic components, precision small gears, and various bearings. The high-temperature property of QTi6-1 alloy is better than that of beryllium bronze, and it can replace elastic components used as precision instruments and meters, such as the vibrating plate and diaphragm of the vibration converter, the contact elastic element of ultrahigh frequency standards, travel switch shrapnel, and high-performance connectors for new energy vehicles/electronic products. It is estimated that by 2035, the QTi6-1 alloy will replace approximately 70% of beryllium copper alloy materials.

3.4 Advanced copper matrix composites

Copper-based composite materials with high strength, high conductivity, high temperature resistance, electrical corrosion resistance, and electromagnetic shielding resistance are urgently required for the manufacture of many high-end applications, including phased array radar, high-power high-frequency pulsed magnetic fields, high-power electronic device packaging, liquid hydrogen/liquid oxygen rocket engine lining, ultrahigh voltage switch contacts, and welding electrode contacts.

New-generation copper–iron electromagnetic shielding materials (Fe content of 5%–40%) are key for the manufacture of new displays. These materials possess high electrical conductivity, good heat dissipation, and electromagnetic shielding function. They are widely used owing to their electromagnetic compatibility in computers, communications, automobiles, electronics, aerospace, and aviation; additionally, they are used as an electromagnetic field shielding material in medical equipment, hospitals, etc., as well as in communication, and electric power fields.

Graphene or nano-ceramic particles have been used to form copper-based composite materials with specific functions. The Cu–Al_2O_3 dispersion-strengthened copper alloy exhibits excellent high-temperature softening resistance and is widely used in microwave tube cavities, launch tube grid support rods, traveling wave tube slow-wave wires, resistance welding electrodes in radar, electronic countermeasures, remote control telemetry, particle accelerators, etc.

In electrical processing, the use of tungsten copper alloy as a contact material has become mainstream. Tungsten copper alloys are relatively inexpensive and exhibit high thermal conductivity, electrical conductivity, heat resistance, and current corrosion resistance; moreover, their coefficient of thermal expansion is low. As such, they fulfill the performance requirements of high power, high voltage, and high current contact materials. They are widely used as a substrate material and chip heat dissipation material in large-scale integrated circuits.

3.5 High-quality ultrafine conductive copper alloy wire

Ultrafine conductive copper alloy wires are used as key materials to prepare integrated circuit packaging wires, micro-motor transmission wires, high-frequency ultrafine coaxial wires, high-speed broadband transmission cables, communication terminal transmission wires, and medical precision wires. Currently, ultrafine copper wires include primarily Cu–Ag and Cu–Sn alloys. Microelectromagnetic wires are extremely important current carriers in electronic components. Their conductive core must possess extremely high conductivity and good mechanical properties to fulfill the manufacturing process requirements of electronic components. They are primarily used in micromotors, relays, electronic transformers, transformers, solenoid valves, and intelligent robots, as well as in transportation, instrumentation, national defense, military applications.

Ultrafine wires such as oxygen-free copper and silver–copper alloys are key materials for micromotors used in high-technology industries. For example, for micro-motor coil windings and electromagnetic wire cores, the diameter of the wire is generally less than 80 μm, which is difficult to prepare and process. With the improvement of domestic raw material preparation technology and equipment capabilities, research regarding the preparation of ultrafine wires with a diameter of less than 30 μm has progressed significantly. It is estimated that by 2035, more than 50% of imported products will be substituted by domestically produced products.

3.6 High-strength and high-conductivity die-casting copper alloy material

Currently, the electricity consumption of various electric motors accounts for approximately 60% of the total domestic electricity consumption. Most squirrel-cage three-phase asynchronous motors use cast aluminum rotors. They are large, consume a significantly amount of energy, low in efficiency, and contribute significantly to motor power loss, thereby severely restricting motor efficiency. Copper possesses good electrical conductivity, heat dissipation, and wear resistance. Substituting cast copper rotors for cast aluminum rotors is a feasible direction for

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the development of ultrahigh-efficiency motors. The cast copper rotor under development has a speed of less than 3000 r/min and can be used in industrial motors such as reducers and water pumps; however, unstable relevant preparation processes and low yield rates hinder their further development, and key technologies involved remain to be understood. In terms of electric vehicles and motors for medium and main shafts, because their speed is higher than 8000 r/min, more stringent requirements such as high density and high strength have been proposed for copper rotors. In the future, copper alloy die-casting materials that can maintain a high electrical conductivity and have high yields and tensile strengths must be developed.

3.7 Ultrathin rolled copper foil for electronics

Flexible circuit boards are indispensable in organic light-emitting diode (OLED) screens, and rolled copper foils are important for manufacturing shielding materials, flexible printed circuit boards, and graphene transparent conductive films. Currently, OLED screens are widely adopted in mobile phones. In the future, with the popularization of wearable electronic equipment, high-resolution display devices, folding screens, smart medical care, unmanned driving, and other technologies, the use of rolled copper foils will increase owing to the extremely high-performance requirements of flexible circuit boards.

According to the statistics of the China Electronic Materials Association, in 2016, the national output of flexible copper clad laminate reached 5.464×10^7 m^2, of which the use of rolled copper foil was approximately 4600 t with an average annual growth rate of 19.9%. In 2017, the global rolled copper foil output was 6.9×10^4 t, whereas the total output from major Chinese companies (CNMC Albetter Copper and Aluminum Co., Ltd., Shandong Tianhe Rolled Copper Foil Co., Ltd., Lingbao Jinyuan Chaohui Copper Co., Ltd., and Suzhou Futian Metal Co., Ltd.) was only approximately 7×10^3 t. Based on this estimate, by 2035, 40% of foreign materials will be replaced by the country's high-performance rolled copper foils.

3.8 Environmentally friendly and easy-to-cut copper alloy materials

Lead brass is widely used in electronic and electrical applications, water pipe faucets, valve bodies, clocks, locks, toys, connectors, and wear parts. Lead is a toxic element. Many countries have established relevant laws to restrict the use of lead brass in electrical and electronic equipment and water supply systems. The development of environmentally friendly, free-cutting Cu alloys has become an inevitable development trend. The existing supply substitutes are bismuth brass and silicon brass. Bismuth brass, such as C89XXX (USA), BZ5/BZ3 (Mitsukoshi Metal Co., Ltd., Japan), HB-20 (Zhejiang Hailiang Co., Ltd.), HBi60 (Sichuan Xinju Mining Resources Development Co., Ltd.), and ZHBi87 (Ningbo Boway Alloy Material Co., Ltd.), are expensive and can exhibit stress cracking and stress corrosion. Silicon brass, such as ECO BRASS (Mitsubishi Shindoh Co., Ltd.) as well as HSi80-3, HSi75-3 (China), have a copper content of 70%–80% and are relatively expensive. Other materials, such as antimony brass, magnesium brass, phosphor–calcium brass, and graphite brass, have not yet been widely promoted and applied.

The future development trend of environmentally friendly free-cutting copper alloys is to develop low-cost copper alloys with excellent machinability. It is estimated that by 2035, 60% of electrical and electronic equipment and water supply systems will be substituted by environmentally friendly free-cutting copper alloys.

4 Research and development trends and domestic problems of advanced copper alloy materials

4.1 Technology research and development trends

In recent years, the overall level of domestic high-performance copper alloys and their preparation technology have progressed significantly. The types of high-performance copper alloy products with independent intellectual property rights have increased, and the installation and processing of copper alloy materials have approached the advanced international level. The development trends of the research, development, and industrialization of advanced copper alloy materials present the following characteristics:

(1) From a single-performance requirement to a multifunctional characteristic requirement. For example, copper-based materials with high thermal conductivity and high electromagnetic shielding performance should fulfill the demand for conductor materials in high-precision fields such as pulsed strong magnetic field systems and particle acceleration electromagnetic transmitters. Furthermore; the 380 km/h high-speed railway power grid contact wire must exhibit higher strength, wear resistance, and fatigue resistance, in addition to high electrical

conductivity. Meanwhile, the copper alloy for the lead frame of very large-scale integrated circuits must exhibit high strength, high electrical conductivity, heat resistance, bending resistance, ease of etching, and other characteristics.

(2) Fine, thin, long, and high-precision copper processing materials are being developed. The demand for ultrafine wires, ultrathin belts, thin-walled tubes, ultralong tubes, ultralong tapes, threaded tubes, special-shaped tubes, special-shaped belts, and other products continues to increase. For example, the lead frame embodies the development trend of multipin, high density, ultrathin, and miniaturization.

(3) High purification of copper. The copper content of industrial copper has been increased from 99.9% to 99.95%, and then to 99.99% or higher, to improve the electrical and thermal conductivity of the material. Ultrapure copper with a copper content of 99.9999% minimizes the effects of impurities on the electrical and thermal conductivity.

(4) Material composites. The potential of a single material strengthening method is limited, and the use of composite methods to further improve the comprehensive performance of copper has become a research focus. Examples include adding second-phase particles, whiskers, or fibers into copper alloys to strengthen the copper matrix and develop new multifunctional copper-based composite materials, which are important for the design of high-performance copper alloys and practical applications in the high-technology field.

4.2 Problems

Although China is the largest producer of copper alloy materials in the world, it is still lagging behind in terms of the relevant technology. High-performance copper alloys are still imported for use in domestic aerospace, electronic information, marine engineering, high-end equipment, and many other high-technology fields. Domestic copper alloy material manufacturers are abundant; however, they are low in industrial concentration, weak in product competitiveness, and meagre in industry profits; hence, they cannot support the development of high-technology industries. The main issues in the copper alloy material industry are as follows:

(1) High-performance copper alloy materials have few varieties and grades, and the overall performance of some high-performance copper alloys is generally lower than that of similar imported products. For example, the number of independently developed and produced Cu–Ni–Si and Cu–Cr–Zr lead frame strips is low.

(2) The stable production capacity of large-scale and high-quality copper alloy products must be improved urgently. For example, the performance stability, surface quality, and comprehensive yield rate of high-precision elastic copper alloy strip products require further investigations.

(3) The processing of high-performance copper alloys results in significant environmental pollution and severe resource wastage; meanwhile, the high-efficiency and short-process preparation technology is not yet mature, and the product quality and performance must be improved.

(4) The lack of independent manufacturing technology for high-end production equipment limits the development of new products. For example, most high-precision foil production equipment are imported.

(5) Some high-end copper alloy materials lack independent intellectual property rights and public research and development platforms. The construction of databases pertaining to material performance, production technology, standards, and specifications is lagging behind.

(6) The large-scale homogenization preparation technology of ultrahigh purity, ultralow oxygen content oxygen-free copper require further improvements. The preparation technology of high-precision, large-diameter, and long-life corrosion-resistant copper–nickel alloy must be further improved.

5 Development path of advanced copper alloy materials in China

5.1 Medium- and long-term development goals

During the 14th Five-Year Plan period, in response to the significant demand for high-end equipment to fabricate high-performance, high-precision copper and copper alloy plates/strips/foil, tubes, rods, and wires, key breakthroughs are necessitated in product performance improvement, green manufacturing, as well as industrial upgrading and integrated innovation in the advanced copper alloy material industry. Additionally, the demonstration, popularization, and application of advanced copper alloy materials must be promoted in key areas of the national economy. New-generation ultrahigh-strength and high-conductivity copper alloys as well as their composite materials must be developed to further improve the performance stability and output of high-end copper alloy products. It is expected that after 5–15 years of research and development, a completely green and

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high-performance manufacturing industry system for advanced copper alloy materials will be built, and the overall technical level will be advanced internationally.

Adjust the industrial structure and promote the green, high-end, and intelligent development of advanced copper alloy materials. (1) Focus on the adjustment and optimization of product positioning, adhere to the path of green and high-end development, strive for high-performance and high-precision, improve product quality, protect the domestic high-end market, and promote exports. (2) Integrate fragmentation technology and establish a large system database for copper alloy material design, processing, equipment, and application. (3) Through technological research and innovation, realize the localization of high-end copper alloy products and eliminate the situation in which advanced copper alloy raw materials are controlled by others; increase the application proportion of products in major engineering fields, and increase the added value of products.

Improve the independent innovation system and promote sustainable development of high-performance copper alloy materials. (1) Through independent research and development of advanced copper alloy systems, preparation, and processing technologies, improve the supporting industrial chain and establish an independent and innovative research, development, and production platform. (2) By further integrating resources, strengthen the cultural construction of an advanced copper alloy industry, form an effective interaction mechanism of “production, education, research, application, and management,” and improve the international operation level of advanced copper alloy industrial clusters to achieve a healthy, coordinated, and stable development.

5.2 Key technology analysis

In terms of the innovation and preparation technology of advanced copper alloy materials, to effectively transcend the bottleneck of preparation technology for domestic materials, independent research and development of high-end products, advanced preparation and processing equipment, and technologies should be further strengthened. This involves a series of key technologies, as presented below:

(1) Construction of an advanced copper alloy system. Perform the integrated design of advanced copper alloy materials/processes/structures forms an advanced copper alloy material system with intellectual property rights and a new preparation technology system; build advanced copper alloy innovation platforms, analytical test evaluation (standard) platforms, and industrialization demonstration platforms in the form of national key laboratories, engineering technology centers, and testing centers to support the construction of independent innovation capabilities for advanced copper alloys.

(2) Development and industrialization of key preparation and processing technologies with independent intellectual property rights for advanced copper alloys based on the requirements of major national projects and new industries. The main contents include the following: industrial production technology for high-precision and high-purity oxygen-free copper plates/strips/foils; industrial production technology for Cu–Cr–Zr-based alloy large weight and super long (> 1500 m) contact wires; industrial production technology for Cu–Ni–Si- and Cu–Cr–Zr-based alloys with large-weight (> 8t), high-precision ultrathin frame strips; high density, leak-free, and reliable special preparation technology for dispersion-strengthened copper alloy and electronic packaging materials with high thermal conductivity and low coefficient of thermal expansion; industrial production technology for high-precision, large-scale, and high-corrosion resistance copper alloys; and industrial production technology for long-life, high-wear, and environment-friendly copper alloys. Additionally, a number of advanced copper alloy high-efficiency short-process preparation and processing technologies should be achieved independently at international leading levels, and the overall technological progress of the copper processing industry should be promoted.

6 Suggestions

6.1 Promote overall planning and integrated development of “production, study, research, use, and management”

Guided by policies and national science and technology planning, a collaborative mechanism of “production, study, research, use, and management” should be implemented by copper alloy preparation and processing enterprises, scientific research institutes, and application units. Other suggestions include the following: (i) focus on the advantages of “production, study, research, and use”; (ii) achieve breakthroughs in the key preparation and processing technologies for the basic raw materials of high-end copper alloys that restrict major projects and emerging industries domestically; (iii) promote the establishment of a leading copper alloy manufacturing power;

(iv) establish and improve four types of platforms, namely "technology research, development, and innovation," "talent training and introduction," "information and exchange," as well as "policy support and guarantee" to provide reliable and continuous technical and talent support for the development of advanced copper alloy industrial clusters; and (v) establish national industrial development zones.

6.2 Improve equipment development, technology research and development, and market development capabilities

China should learn from advanced international experiences and development processes, rely on independent technological innovation, and establish industry big data to drive the intelligent control process of copper and copper alloy material manufacturing. With the development of industry-related equipment as the core, China should focus on advanced continuous casting and rolling (continuous extrusion) units, continuous drawing and continuous annealing units, continuous drawing and continuous plating units, ultrafine wire drawing and wire annealing plating/coating units, improving production capacity and production efficiency, reducing energy consumption and raw material loss rate, improving product performance and quality stability, and increasing market competitiveness and market share.

6.3 Strengthen research and formulation of product standards

To fulfill the requirements of high-end manufacturing for the competitive performances of advanced copper alloy materials, China should establish and improve a standards system for advanced copper alloy material products and their production technology. Furthermore, China should establish national or industrial technical standards for new products such as ultrafine copper wires (including tinned wires and enameled wires) and special copper-based composite materials, improve standards and methods for copper resource recycling, strengthen the industry regulation from the source, and ensure the sound and sustainable development of the industry.

6.4 Establish advanced training system for copper alloy technologies

China should enrich academic/technical seminars, strengthen exchanges among technical experts, young scientific, and technological talents, promote military-civilian collaborative applications, and promote the cooperation of enterprises with different ownership types. Furthermore, China should promote the support of experts to enterprises such that experts can contribute wisdom to product breakthroughs and provide specific technical support in production. An advanced copper alloy talent team should be established by combining the elderly, middle-aged, and young people.

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