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Controlled Preparation of High-entropy Alloys and Their Application in Electrocatalytic CO_2 Reduction Reaction

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Abstract. In recent years, the excessive consumption of non-renewable energy has led to a sharp increase in carbon dioxide levels in the air, causing numerous environmental issues. Therefore, developing new energy sources to replace coal, oil, and other renewable energies is urgently needed. High-entropy alloys (HEAs), as a novel material, can be used as catalysts for electrocatalytic CO_2 reduction reactions, addressing current energy crises and global warming problems. This article first introduces the unique properties of HEAs and why they can serve as catalysts in electrocatalytic CO_2 reduction reactions, focusing on the four major effects of HEAs. It then discusses three methods for preparing HEAs: carbon heat shock, electrochemical methods, and magnetron sputtering. The article highlights the advantages and disadvantages of each preparation method and reviews current research progress. Finally, it summarizes the applications of HEAs in electrocatalytic CO_2 reduction reactions from both noble metal-based and non-noble metal-based perspectives, emphasizing recent research advancements. This article aims to address shortcomings in related academic research and industrial applications, providing a reference for future preparation methods of HEAs and their use in electrocatalytic CO_2 reduction reactions.

Keywords: high-entropy alloys, preparation method, electrocatalytic CO_2 reduction, performance

1. Introduction

With the development of society, non-renewable resources are being excessively consumed. This has led to a sharp increase in the concentration of carbon dioxide in the atmosphere, resulting in issues such as desertification of land and global climate warming. Against the backdrop of global efforts to combat climate change, carbon neutrality has become one of the primary measures taken by governments, businesses, and even individuals worldwide to address global warming. In 2023, China consumed a total of 5.132 billion tons of coal and 756 million tons of oil, leading to carbon dioxide emissions from energy-related sectors reaching 10.5 to 12.6 billion tons, accounting for over 80% of total CO_2 emissions.[1] Therefore, developing new energy sources to replace traditional coal and oil is urgently needed to reduce carbon emissions. Electrocatalytic reaction, (EC reaction) refers to the process where chemical reactions are promoted by applying an external current or voltage

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under the influence of a catalyst. Through these reactions, efficient energy storage and conversion can be achieved, thereby addressing issues such as the energy crisis and global warming. Electrocatalytic reactions are primarily divided into hydrogen evolution reactions (HER), oxygen absorption reactions (OER), nitrogen reduction reactions (NRR), and carbon dioxide reduction reactions(CO_2RR). CO_2RR is the reaction that converts carbon dioxide into useful carbon-based compounds (such as methanol, ethylene, methane, etc.) through electrocatalysis. Through this reaction, not only can the accumulation of CO_2 in the air be alleviated, but it also produces various organic and inorganic products (such as methane, ethylene, methanol, acetic acid, etc.), which have significant application value in energy and chemical industries. The catalyst required for electrocatalytic CO_2 reduction reactions is crucial for their success, affecting the efficiency, stability, and selectivity of the reaction. Therefore, the choice of catalyst is a critical factor influencing the performance of electrocatalytic CO_2RR.

HEAs are alloys formed using five or more metals in equal or approximately equal amounts, with the atomic ratios of each element generally ranging from 5% to 35%.[2]The mixing configurational entropy (Smix) can be used to define HEA. Equation (1) is its calculation formula.

$$S_{mix} = -R\sum X_i \ln X_i \tag{1}$$

If the HEAs are solid solution and the amount of component is equal, the calculation of S_{mix} can be simplified to equation (2)

$$S_{mix} = R\ln n \tag{2}$$

In the formula: R is the gas constant; X_i is the molar fraction of component i; n is the number of element types. Generally, alloys with $n\geq5$ are classified as HEAs. Considering the entire alloy system, the mixed Gibbs free energy (G_{mix}) can be calculated using equation (3)

$$G_{mix} = H_{mix} - TS_{mix} \tag{3}$$

In the formula, S_{mix} represents the Enthalpy of mixing.

Thermodynamic analysis reveals that maintaining a constant mixing enthalpy (H_{mix}) while increasing its magnitude reduces the system's Gibbs free energy, thereby enhancing thermodynamic stability and promoting the formation of homogeneous solid solutions. This energetic stabilization favors complete atomic-scale mixing of constituent elements. High-entropy alloys predominantly crystallize in simple structural motifs, most commonly exhibiting either face-centered cubic (FCC), body-centered cubic (BCC), or hexagonal close-packed (HCP) configurations. Different atoms randomly occupy lattice positions, forming simple solid solutions. Due to its unique structure, it has many properties that are different from those of conventional alloy materials. These materials demonstrate superior catalytic performance due to their unique synergistic characteristics. High-entropy alloys (HEAs) are governed by four fundamental phenomena: (1) the entropic stabilization effect, which enhances phase stability; (2) the multicomponent synergy effect, enabling tailored electronic configurations; (3) severe lattice strain from atomic size mismatch; and (4) kinetically hindered atomic diffusion, which preserves metastable states under operational conditions [3,4]. The high-entropy effect provides the system with a larger mixing configuration entropy, thereby

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enhancing its stability under extreme operational environments characterized by elevated temperatures (>800 °C), high-pressure regimes (10-100 atm), and aggressive chemical media, ensuring that it remains active as a catalyst in various environments. The cocktail effect highlights the unique properties resulting from the synergistic action of multiple elements, which can be altered by changing the alloy's elemental composition to control the course of catalytic reactions, thus influencing catalytic performance. Additionally, the cocktail effect promotes a more complex lattice structure in materials, which helps improve their mechanical properties under extreme conditions. The lattice distortion effect is due to varying atomic sizes. Therefore, People often improve the performance of catalysts by utilizing lattice distortion effects. Moreover, lattice distortion reduces the rate of atomic motion and leads to the hysteresis diffusion effect in HEAs. The reason why high-entropy alloys can function as catalysts under both acidic and basic conditions is due to their hysteresis effect and high-entropy effect. Thus, HEAs are important materials for electrocatalytic CO_2 reactions.

This article summarizes three methods for controllably preparing HEAs: the carbon heat shock method, the electrochemical method, and the magnetron sputtering method. It also introduces the application of HEAs in electrocatalytic CO_2 reduction reactions from both noble metal-based and non-noble metal-based HEAs, aiming to provide a reference for the future preparation of HEAs and their applications in electrocatalytic CO_2 reduction reactions.

2. Preparation methods of high entropy alloys

Controllable preparation of HEAs is the foundation for reasonably utilizing HEAs as electrocatalysts for CO_2 reduction. To this end, we have compiled three methods for controllably preparing HEAs: the carbon heat shock method, the electrochemical method, and the magnetron sputtering method.

2.1. Carbon heat shock method

The carbon heat shock method refers to loading HEA nanoparticles (NPs) onto a carbon substrate through thermal shock, followed by controlling the parameters of the carbon heat shock (CTS) (substrate, temperature, impact duration, and heating/cooling rate) to synthesize multi-component nanograins with desired chemical composition, size, and phase (solid solution, phase separation). The main principles include the carbon heat reaction principle, high-temperature mixing principle, and rapid cooling principle. The carbon heat reaction principle involves using carbon as a reductant to undergo redox reactions with metal salts, reducing metal ions in the salt to metallic atoms, thus providing elemental metals for alloy formation. The high-temperature mixing principle involves ultra-high temperatures that give metal atoms sufficient energy to overcome inter-elemental immiscibility gaps, increasing atomic diffusion rates and mobility, allowing multiple metal atoms to mix thoroughly. The rapid cooling principle involves rapid cooling that "freezes" metal atoms in a uniformly mixed state within a short time, inhibiting phase separation between incompatible elements, maintaining the alloy in a high-entropy state, and forming a single solid solution phase.[5]

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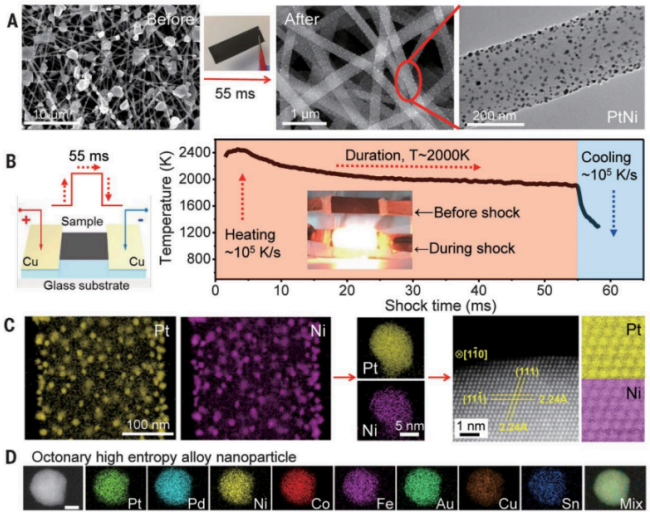

Figure 1: CTS synthesis of HEA-NPs on carbon supports. (A) Pre- and post-CTS characterization: (left) precursor salt particles on carbon nanofibers (CNFs) and (right) uniformly dispersed PtNi nanoparticles after rapid thermal processing. (B) Schematic of the CTS procedure and the transient temperature profile (duration: 55 ms). (C) Structural and compositional analysis of binary PtNi NPs: (top) low-magnification HAADF-STEM image and elemental maps; (bottom) atomic-resolution HAADF image with corresponding elemental distribution. (D) Multielemental mapping of an octonary HEA-NP (Pt, Pd, Ni, Co, Fe, Au, Cu, Sn), demonstrating compositional homogeneity at the nanoscale. Scale bars: 10 nm

Yao et al.[5] first prepared HEAs using the carbon-thermal shock method. Figure 1 illustrates the synthesis protocol, which employs an ultra-rapid thermal processing approach for metal precursors deposited on carbonaceous oxide substrates. The process features extreme temperature conditions (~2000 K) with precisely controlled thermal pulses lasting 55 milliseconds and a heating rate of about 105 K/s), to produce HEA NPs containing up to eight different metal elements. The MMNPs synthesized by CTS have a narrow size distribution and are uniformly dispersed on the carbon support.

The synergistic effect of elevated temperatures and liquid metal catalysis promotes rapid atomic-scale rearrangement through continuous particle fragmentation and coalescence processes, yielding homogeneous multielemental mixtures. The precisely controlled quenching rate subsequently regulates the thermodynamic equilibrium state, allowing for the crystallization of single-phase solid solution nanoparticles. Building upon this methodology, Qi and colleagues [6] successfully fabricated both thin film and carbon-supported nanoparticle systems encompassing various compositional complexities, including monometallic (Pt), bimetallic (PtRu), trimetallic (PtRuIr), and higher-order multimetallic (PtRuIrRh, PtRuIrRhPd) configurations using magnetron co-sputtering and carbon-thermal shock synthesis methods. They characterized the samples using various techniques and studied their electrochemical behavior and stability under acidic and alkaline media with a wide potential window using cyclic voltammetry (CV) and on-line ICP-MS. In CV, by measuring the potential difference between the working electrode and the reference electrode over time, they found that the area of CV significantly increases with the addition of other elements. This indicates that the amount of alloy components significantly enhances the electrochemical active surface area (Electrochemical Active Surface Area, ECSA). Recently, Wang et al.[7] in order to protect the oxygen-containing functional groups in CCF, used cellulose paper as a carbon support

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and employed the carbothermic reduction method, thereby constructing a core-shell heterogeneous interface for the HEAs. Through this enhanced strategy, CCP/HEAs composites prepared at a manganese element molar ratio of 35% (CCP/HEAs-Mn 2.15) can effectively absorb electromagnetic waves (EMW), reducing EMW pollution and developing EMW shielding devices.

The carbon heat shock method is versatile, adjustable, and potentially scalable.[5] With a maximum temperature of 2000 to 3000 K, which exceeds the decomposition temperatures of most metal salts, it can react with most metallic substances (versatility). By precisely adjusting shock parameters (temperature, impact time, and heating rate), the structure of HEAs can be regulated (adjustability). The rapid synthesis process (completed in milliseconds) and high energy efficiency (immediate heating through electric pulses) enable the high-speed and large-scale production of high-quality nanoparticles, making it suitable for mass production (potential scalability). However, this method requires sophisticated equipment capable of generating high temperatures and rapid cooling to achieve the carbon heat shock process. Additionally, its process parameters are difficult to control; factors such as temperature and cooling rate during the carbon heat shock process significantly impact the quality and performance of the final product. Small changes in these parameters can lead to significant differences in material properties, necessitating precise control and extensive experimentation to determine optimal parameters. This results in high equipment costs and stringent requirements for stability and safety.

2.2. Electrochemical method

Electrochemical preparation methods mainly include electro-deposition and molten salt deoxidation. The principle of electro-deposition is to control the composition of the electrolyte and electrical parameters (such as current density and voltage) to deposit various metal ions, forming a HEA coating. In the process of molten salt deoxidation, multiple metal oxides to be reduced are mixed and pressed into the cathode, while an inert electrode (such as graphite or platinum) serves as the anode, all immersed in a high-temperature molten salt system. When the power supply is connected, the anode undergoes oxidation, releasing oxygen; the cathode then undergoes reduction, where oxygen ions from the metal oxides receive electrons and are reduced back into metal atoms. These different metal atoms generated at the cathode surface diffuse and mix, ultimately forming a HEA.

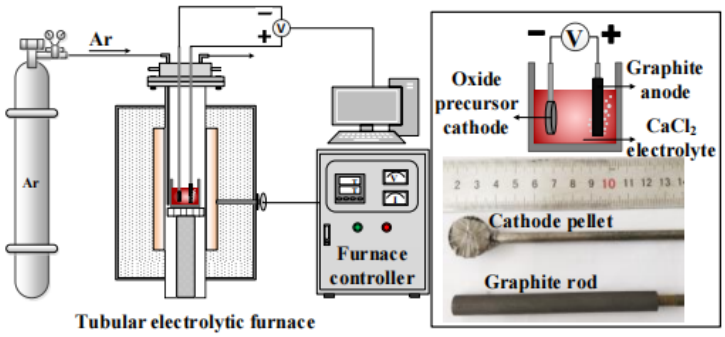

Figure 2: Schematic diagram of experiment platform, electrolysis cell, and appearance of anode and cathod [8]

Soare et al.[8] were the first to successfully prepare Al-Cr-Fe-Mn-Ni and Al-Cr-Cu-Fe-Mn-Ni through the electrodeposition method. Microstructural characterization revealed well-consolidated diamond films composed of monodisperse particles (500 nm-4 μm), as evidenced by SEM analysis.

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XRD patterns confirmed the amorphous nature of the deposited films. Under an inert Ar atmosphere, different temperatures were used for annealing, and the BCC structure of the films was characterized by XRD. The adhesion of the alloys on the substrate was determined using scratch tests, yielding higher values for the Al-Cr-Cu-Fe-Mn-Ni alloy. Yang et al.[9] successfully prepared HEAs through molten salt deoxidation and analyzed the phase transformation of metal oxides into HEAs at different electrolysis times using XRD, SEM, and energy dispersive spectroscopy (EDS). The apparatus for preparing HEAs is shown in Figure 2. The results show that the formation process of CoCrFeNi alloy HEEA is divided into two stages: rapid deoxidation and deep deoxidation. In the rapid deoxidation stage, 93.93% (by mass) of oxygen in the sintered oxide pellets was removed within 1 hour, with an electrical efficiency of 89.95%. After electrolysis for 15 hours in the second stage, the oxygen content in the product was 0.26 wt%, but the electrical efficiency was only 17.93%. Recently, Li et al.[10] successfully prepared RHEAs using electrochemical methods and investigated the effects of reaction temperature, raw materials, and protective layers on reducing carbon pollution. They used TiO_2, ZrO_2, HfO_2, Nb_2O_5, and Ta_2O_5 as raw materials, which were ball-milled, dried, and pressed to form oxide precursors for use as cathodes. Electrolytic reduction reactions were carried out in a $CaCl_2$ molten salt system using graphite anodes and solid oxygen ion conductive membranes (SOM@C/Sn) containing graphite and tin as anodes. Various testing methods were employed to characterize and analyze the products.

Electrodeposition offers distinct advantages over other thin-film fabrication methods, including: minimal infrastructure requirements, eliminating the need for expensive or sophisticated equipment; broad material compatibility, utilizing commercially available precursors; enhanced conformal coverage, enabling uniform deposition on substrates with intricate geometries; energy-efficient operation, achievable at ambient or near-ambient temperatures. Moreover, test results from SEM, XBD, and scratch tests indicate that electro-deposition is a very promising method for preparing HEAs.[9] For the molten salt electro-deoxidation method, compared to traditional methods for preparing HEAs, it has a lower reaction temperature and a simpler process flow. Additionally, the significant differences in physical and chemical properties between components can easily lead to segregation during the melting process, which is avoided by the electrochemical method for preparing HEAs.[10]

2.3. Magnetron sputtering method

Magnetic sputtering utilizes a magnetic field to confine the plasma, successfully enabling the preparation of high-entropy alloys. Its fundamental principle involves accelerating the plasma in the atmosphere into high-energy particles with an applied electric field and alternating magnetic fields, which then bombard the target material's surface.

Upon energy transfer, surface atoms are ejected from the target lattice due to momentum exchange, subsequently depositing onto the substrate to form a thin film. This method features low-temperature preparation, precise component control, and high uniformity, making it a universal approach for the preparation of electronic components, optical coatings, and HEA films. The magnetron sputtering method for preparing HEAs mainly includes four techniques: DC magnetron sputtering, RF magnetron sputtering, ion beam magnetron sputtering, and pulsed magnetron sputtering.

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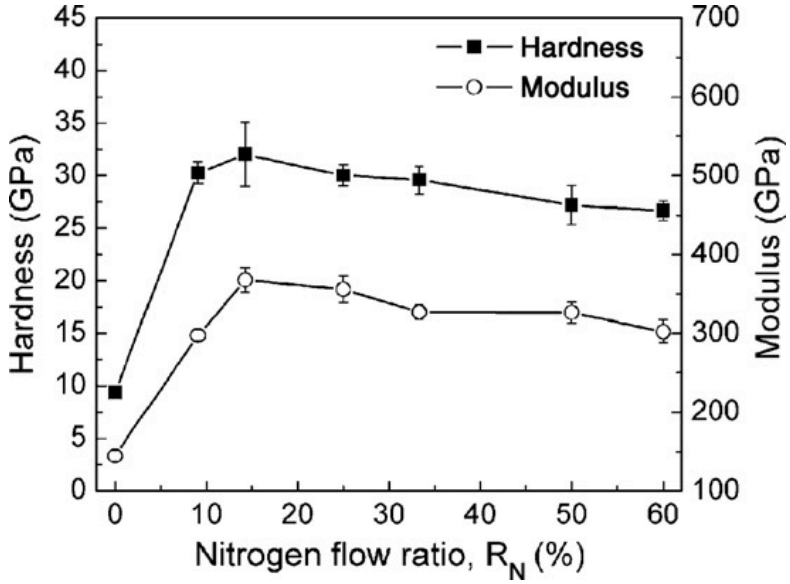

Figure 3: Mechanical properties of multi-component AlCrTaTiZr nitride coatings: Nanomechanical response to nitrogen flux variation during deposition [11]

Lai et al.[11] first used the single-target magnetron sputtering method to prepare equimolar AlCrTaTiZr multicomponent HEA nitride thin films and characterized the elemental composition, microstructural features, and mechanical property parameters of the multicomponent nitride coatings, analyzing their microstructure and mechanical performance. The results show that, as shown in Figure 3, with the increase in N_2 flow ratio, the deposition rate of the nitride film gradually decreases, while the hardness and elastic modulus of the nitride film increase, reaching maximum values of 32 and 368 GPa at RN = 14%. Liu et al.[12] used DC magnetron sputtering technology, employing FeCoNiCuVZrAl HEA as the target material and Ar and N_2 as the source gases, to prepare multicomponent amorphous nitride thin films. Systematic studies have shown that the thickness and roughness of the amorphous films are closely related to the concentration of N_2 in the mixed atmosphere. As the N_2 flow ratio was increased from 0% to 50%, the film thickness decreases, and the roughness first decreases and then increases. Poliakov et al.[13] prepared CoCrFeNiTix thin films on Si/SiO_2 substrates using magnetron sputtering with multi-component targets made from hot-pressed mixed pure metal powders. They analyzed the film structure, composition, and properties through various testing methods, including XRD, SEM, TEM, EDX, and AES. A semi-automatic probe station was used to test the temperature dependence of resistance, exploring its potential as a resistive element in microelectronic devices. The results showed that the room-temperature resistivity of the film was 2.37×10^{-6} Ω·m. In the first heating test, the resistivity decreased with temperature initially, then increased and decreased again. Annealing stabilized the resistivity and improved contact performance. From-60 °C to 130 °C, the TCR varied linearly with temperature, decreasing from-78 ppm/°C to-6.6 ppm/°C.

Magnetron sputtering can precisely control the composition of HEA thin films. By adjusting the target material composition and sputtering parameters, it is possible to achieve precise control over the elemental ratios in the film. Moreover, the surface of the fabricated films is smooth and flat, with a dense structure and few defects, which enhances the application performance of HEA thin films in fields such as microelectronics and optics. Compared to traditional high-temperature melting, magnetron sputtering has a lower preparation temperature, avoiding the impact of high temperatures

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on the properties of the base material. This reduces the volatilization of HEA components and element segregation during high-temperature treatment, ensuring the stability of alloy composition and properties, and expanding the range of base materials that can be used. Finally, this method is relatively simple, with mature equipment, making it easy for industrial production. By optimizing process parameters, large-scale continuous production can be achieved, improving production efficiency and reducing costs, laying the foundation for the industrial application of HEAs.

3. The role of high entropy alloys in carbon dioxide reduction reaction

HEAs, as catalysts with excellent properties, play an important role in the electrocatalytic CO_2RR. We will introduce HEA materials based on precious metals and non-precious metals respectively in the electrocatalytic CO_2RR.

In the study of HEAs based on non-precious metals for electrocatalytic CO_2 reduction, He et al. prepared Cu/X (X = Pd, Ag, Au) catalysts using thermal evaporation coating technology[14]. They analyzed the structure, composition, and electronic properties of the catalysts through various characterization methods. The CO_2RR performance and reaction mechanisms were studied via multiple electrochemical tests and in-situ spectroscopic techniques, with DFT calculations providing additional insights. In-situ Raman spectroscopy and ATR-SEIRAS showed that CuAg-4.33% is more favorable for adsorbing and stabilizing $^*CO$ intermediates, promoting C-C coupling. On this basis, He et al. prepared an ion liquid-modified copper nanowire catalyst [Bmim][PF_6]@A-CuNWs using a simple method[15]. They analyzed the structure, composition, and electronic properties of the catalysts through various characterization methods, studied the CO_2 electroreduction performance of the catalysts through electrochemical tests, and explored the reaction mechanisms using in-situ Raman spectroscopy and in-situ Fourier transform infrared spectroscopy (FTIR). DFT calculations were used to assist in the analysis. The results showed that, as shown in Figure 4, A-CuNWs exhibited high C_2H_4 selectivity in the CO_2 electroreduction reaction (with a Faraday efficiency FE of 71.1%). And the product selectivity of [Bmim][PF_6]@A-CuNWs has significantly changed, with CH_4 selectivity greatly increased (FE reaching 67.2%) and C_2H_4 selectivity dropping to 11.1%. Both catalysts exhibited good stability during long-term electrolysis. Recently, He et al. conducted DFT calculations to figure out the function of particle size on the electronic structure of HEAs and the adsorption energy of key intermediates[16]. They constructed models of Cu (111) and different sizes of CuAgPdCoNi HEAs, calculated the Gibbs free energy for $^*CO_2$ hydrogenation to form $^*COOH$, and found that smaller CuAgPdCoNi-S1 had a more favorable $\delta G_{*CO2\text{-}COOH}$ value. This indicates that small-sized HEA with optimal electronic properties is beneficial for CO_2 activation and the formation and conversion of key reaction intermediates, thereby enhancing CO_2RR performance.

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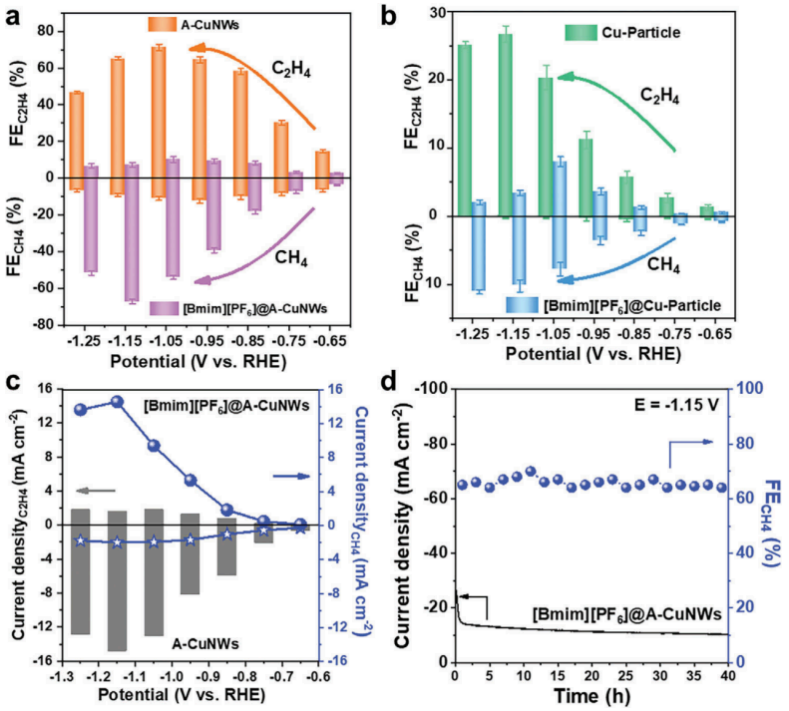

Figure 4: a) FEs of C2H4 and CH4 on A-CuNWs and [Bmim][PF6]@A-CuNWs at different applied potentials. b) FEs of C2H4 and CH4 on Cu-Particle and [Bmim][PF6]@Cu-Particle at different applied potentials. c) Current densities of C2H4 and CH4 on A-CuNWs and [Bmim][PF6]@A-CuNWs at different applied potentials. d) Chronopotentiometry test and the corresponding FE of CH4 on [Bmim][PF6]@A-CuNWs [15]

In the field of studying HEAs based on precious metals as electrocatalysts for CO_2 reduction, Shi et al. successfully reported a mechanochemically-assisted liquid metal reduction approach for the ambient-temperature fabrication of ultrasmall (<3 nm) Pt-containing HEA nanocatalysts. [16]. The Co-Fe-Ni-Pt-Ta-VxC72 nanoparticles exhibit excellent electrocatalytic activity and stability for both HER and OER, providing a foundation for understanding the electrocatalytic properties of platinum-based HEAs. Building on this, Wu et al. synthesized and revealed the electronic structure of NM-HEA NPs for the first time, with its broad bandgap spectrum originating from the diversity of LDOS[17], which offers possibilities for designing efficient catalysts for complex reactions. Recently, Liu et al. achieved the universal preparation of HEAs (hexagonal PdCuAuAgBiIn HEAAs, heptagonal PdCuAuAgBiInCo HEAAs, heptagonal PdCuAuAgBiInZn HEAAs, octagonal PdCuAuAgBiInCoNi HEAAs, and nonagonal PdCuAuAgBiInCoNiZn HEAAs) for the first time using freeze-thaw methods[18], successfully obtaining a series of highly efficient and stable new CO_2RR electrocatalysts. This high-entropy alloy aerogel, due to its unique three-dimensional network structure, strong intermetal interactions, and abundant unsaturated sites on the surface, provides a new platform for efficient electrochemical CO_2 reduction. At the same time, as shown in Figure 5, the HEA aerogel can optimize the adsorption and desorption of catalyst surface reaction intermediates, inhibit CO poisoning and hydrogen evolution side reactions, and synergistically enhance its CO_2RR catalytic activity, selectivity and stability.

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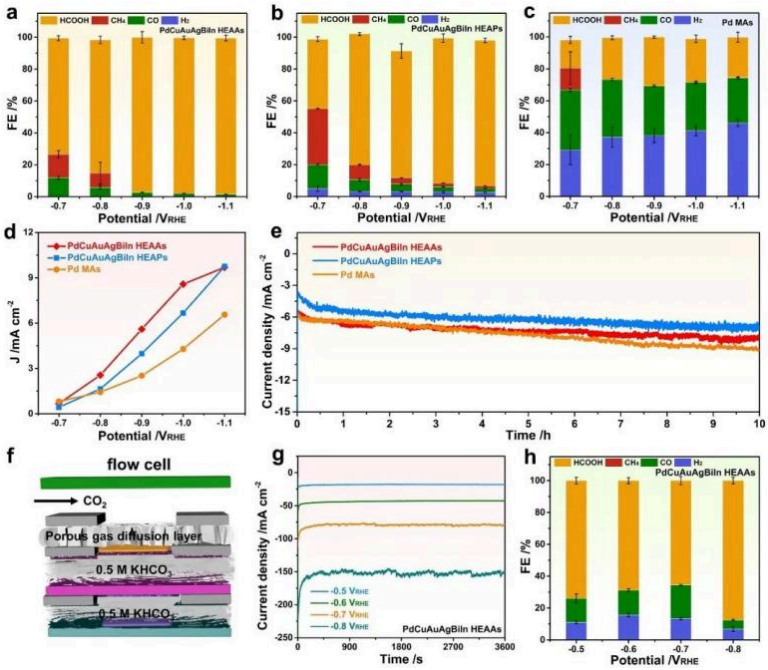

Figure 5: Study of CO2RR performance of PdCuAuAgBiIn HEAAs, PdCuAuAgBiIn HEAPs and Pd MAs [18]

4.Conclusion and outlook

This paper focuses on the study of HEAs in the field of electrocatalytic CO_2 reduction. Due to excessive consumption of traditional energy sources leading to increased CO_2 emissions and climate warming issues, electrocatalytic CO_2 reduction can alleviate these problems and produce valuable products. The unique structure of HEAs makes them important catalysts. As for preparation methods, the carbon heat shock method utilizes principles of carbon heat reaction, high-temperature mixing, and rapid cooling to prepare multi-component nanoparticles, which are versatile, adjustable, and potentially scalable. However, it requires sophisticated equipment, is difficult to control process parameters, and has high energy consumption. Electrochemical methods such as electro-deposition have simple equipment and readily available raw materials, allowing for film formation on complex substrates. Molten salt deoxygenation involves low reaction temperatures and a straightforward process. Magnetron sputtering can precisely control the composition of thin films, resulting in high-quality films that require low preparation temperatures and are easy to industrialize. In applications, Cu/X series catalysts based on non-noble metals and copper nanowires modified with ionic liquids exhibit different product selectivities and good stability in electrocatalytic CO_2 reduction reactions, and small-sized HEAs enhance reaction performance. Noble metal-based HEAs can be prepared through various methods and exhibit excellent catalytic activity, selectivity, and stability.

In future, it is important to figure out the relationship between the composition, structure, and properties of HEA elements. By leveraging theoretical calculations and simulation techniques, we can design HEAs with superior catalytic performance, such as precisely controlling active sites and optimizing electronic structures to enhance the selectivity and activity of CO_2RR. Next, we should investigate ways to improve the long-term stability of HEAs in electrocatalytic CO_2 reduction reactions, studying their structural evolution and performance degradation mechanisms under complex reaction conditions. We can enhance stability through surface modification and composite technologies, expanding practical application scenarios. Finally, we should continuously refine

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existing preparation methods to enhance cost-effectiveness, optimize production throughput, and elevate product performance metrics. Developing new preparation techniques will enable large-scale, high-quality production of HEAs, meeting industrial demands.

References

[1] Fang Yuanqing & Chen Jing. Development and significance of China's new energy technology under the background of carbon peak and carbon neutrality%J Materials Bulletin. 38, 35-40 (2024).

[2] Xin, Y. Xin, Y. et al. High-Entropy Alloys as a Platform for Catalysis: Progress, Challenges, and Opportunities. Acs Catalysis 10, 11280-11306, doi: 10.1021/acscatal.0c03617 (2020).

[3] Wang, L. Wang, L. et al. Tunable intrinsic strain in two-dimensional transition metal electrocatalysts. Science 363, 870-+, doi: 10.1126/science.aat8051 (2019).

[4] Li, J. Li, J. et al. Anisotropic Strain Tuning of L1< sub> 0< /sub> Ternary Nanoparticles for Oxygen Reduction. Journal of the American Chemical Society 142, 19209-19216, doi: 10.1021/jacs.0c08962 (2020).

[5] Yao, Y. Yao, Y. et al. Carbothermal shock synthesis of high-entropy-alloy nanoparticles. Science 359, 1489-1494, doi: 10.1126/science.aan5412 (2018).

[6] Kormanyos, A. Kormanyos, A. et al. Stability of high-entropy alloys under electrocatalytic conditions. iScience 26, 107775, doi: 10.1016/j.isci.2023.107775 (2023).

[7] Wang, H. Wang, H. et al. Spontaneous Orientation Polarization of Anisotropic Equivalent Dipoles Harnessed by Entropy Engineering for Ultra-Thin Electromagnetic Wave Absorber. Nano-Micro Letters 17, doi: 10.1007/s40820-024-01507-0 (2025).

[8] Soare, V. Soare, V. et al. Electrochemical deposition and microstructural characterization of AlCrFeMnNi and AlCrCuFeMnNi high entropy alloy thin films. Applied Surface Science 358, 533-539, doi: 10.1016/j.apsusc.2015.07.142 (2015).

[9] Yang Yu et al. Formation process of CoCrFeNi high-entropy alloy in metal oxide molten salt electro-deoxidation (English)%J Rare Metal Materials and Engineering. 50, 3116-3124 (2021).

[10] Li, P. Li, P. et al. Eliminating carbon contamination with improved one-step electrochemical preparation of refractory high-entropy alloy TiZrHfNbTa. Journal of Materials Science & Technology 163, 132-139, doi: 10.1016/j.jmst.2023.04.019 (2023).

[11] Lai, C. H., Lin, S. J., Yeh, J. W. & Chang, S. Y. Preparation and characterization of AlCrTaTiZr multi-element nitride coatings. Surface & Coatings Technology 201, 3275-3280, doi: 10.1016/j.surfcoat.2006.06.048 (2006).

[12] Liu, L., Zhu, J. B., Hou, C., Li, J. C. & Jiang, Q. Dense and smooth amorphous films of multicomponent FeCoNiCuVZrAl high-entropy alloy deposited by direct current magnetron sputtering. Materials & Design 46, 675-679, doi: 10.1016/j.matdes.2012.11.001 (2013).

[13] Poliakov, M. Poliakov, M. et al. Amorphous/Nanocrystalline High-Entropy CoCrFeNiTi< sub> x< /sub> Thin Films with Low Thermal Coefficient of Resistivity Obtained via Magnetron Deposition. Nanomaterials 13, doi: 10.3390/nano13132004 (2023).

[14] Zhai, Z. Y. Zhai, Z. Y. et al. Heteroatom-induced tensile strain in copper lattice boosts CO< sub> 2< /sub> electroreduction toward multi-carbon products. Carbon Energy 6, doi: 10.1002/cey2.648 (2024).

[15] Cai, H. Z. Cai, H. Z. et al. Ionic Liquid-Induced Product Switching in CO< sub> 2< /sub> Electroreduction on Copper Reaction Interface. Advanced Functional Materials 34, doi: 10.1002/adfm.202404102 (2024).

[16] Shi, W. Shi, W. et al. High-entropy alloy stabilized and activated Pt clusters for highly efficient electrocatalysis. Susmat 2, 186-196, doi: 10.1002/sus2.56 (2022).

[17] Wu, D. S. Wu, D. S. et al. Noble-Metal High-Entropy-Alloy Nanoparticles: Atomic-Level Insight into the Electronic Structure. Journal of the American Chemical Society 144, 3365-3369, doi: 10.1021/jacs.1c13616 (2022).

[18] Li, H. et al. High-Entropy Alloy Aerogels: A New Platform for Carbon Dioxide Reduction. Advanced Materials 35, doi: 10.1002/adma.202209242 (2023).